Airborne Conflict Management (ACM)

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Section 1
Airborne Conflict Management Application Description
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Analysis of Surveillance Requirements to Support Airborne Conflict Management
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Abbreviations

The following abbreviations are used in this document:

ACAD	Assured Collision Avoidance Distance
ACAS	Airborne Collision Avoidance System. (ACAS is the ICAO standard for TCAS)
ANSD	Assured Normal Separation Distance
AOC	Aeronautical Operational Control
ATC	Air Traffic Control
ATM	Air Traffic Management
ATS	Air Traffic Service
ATSP	Air Traffic Service Provider
CAZ	Collision Avoidance Zone
CD	Conflict Detection
CD&R	Conflict Detection and Resolution
CDTI	Cockpit Display of Traffic Information
CDZ	Conflict Detection Zone
CNS	Communications, Navigation, Surveillance
CP	Conflict Prevention
CR	Conflict Resolution
EUROCONTROL	European Organization for the Safety of Air Navigation
FAA	Federal Aviation Administration
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IFR	Instrument Flight Rules
MASPS	Minimum Aviation System Performance Standards
NAC	Navigation Accuracy Category
NAS	National Airspace System
NASA	National Aeronautics and Space Administration

NLR	Nationaal Lucht- en Ruimtevaartlaboratorium National Aerospace Laboratory in the Netherlands.
NM or nmi	Nautical Miles
NIC	Navigation Integrity Category
NTSB	National Transportation Safety Board
R&D	Research and Development
RA	Resolution Advisory
SC	Special Committee
SSR	Secondary Surveillance Radar
TA	Traffic Alert. Notification of traffic which are expected to violate some separation criteria
TCAS	Traffic Alert and Collision Avoidance System (See ACAS)
TCAS I	TCAS system which does not provide resolution advisories
TIS-B	Traffic Information Service – Broadcast Broadcast of traffic information from the ground to aircraft in a format similar to ADS-B.
TORCH	Technical ecOnomical and opeRational assessment of an ATM Concept acHiveable from the year 2005
UTC	Universal Time, Coordinated, formerly Greenwich Mean Time
VFR	Visual Flight Rules
WG	Working Group

Definition of terms

Automatic Dependent Surveillance-Broadcast (ADS-B): ADS-B is a function on an aircraft or surface vehicle operating within the surface movement area that periodically broadcasts its state vector (horizontal and vertical position, horizontal and vertical velocity) and other information. ADS-B is automatic because no external stimulus is required to elicit a transmission; it is dependent because it relies on on-board navigation sources and on-board broadcast transmission systems to provide surveillance information to other users.

Airborne Separation Assurance: Provides the pilots with all the critical information necessary to understand the state and condition of the aircraft and the aircraft's external environment. This includes information on the aircraft's relationship to nearby terrain and obstacles, noise sensitive areas, hazardous weather, traffic, and air traffic management clearances and instructions. *This document only addresses the traffic element.*

Alert: A general term that applies to all advisories, cautions, and warning information, can include visual, aural, tactile, or other attention-getting methods.

Assured Collision Avoidance Distance (ACAD): The minimum assured vertical and horizontal distances allowed between aircraft geometric centers. If this distance is violated, a collision or dangerously close spacing will occur. These distances are fixed numbers calculated by risk modeling and initially will be based on ACAS separation distances.

Assured Normal Separation Distance (ANSD): The normal minimum assured vertical and horizontal distances allowed between aircraft geometric centers. These distances are entered by the pilot or set by the system. Initially the ANSD will be based on current separation standards (and will be larger than the ACAD). In the long term, collision risk modeling will set the ANSD. Ultimately the ANSD may be reduced toward the value of the ACAD.

Collision Avoidance Zone (CAZ): Zone used by the system to predict a collision or dangerously close spacing. The CAZ is defined by the sum of Assured Collision Avoidance Distance (ACAD) and position uncertainties.

Collision Avoidance Zone (CAZ) Alert: Notifies aircraft crew that a CAZ penetration will occur if immediate action is not taken. Aggressive avoidance action is essential.

Conflict: A predicted violation of parameterized minimum separation criteria for adverse weather, aircraft traffic, special use airspace, other airspace, turbulence, noise sensitive areas, terrain and obstacles, etc. There can be different levels or types of conflict based on how the parameters are defined. Criteria can be either geometry-based or time-based. This document only addresses aircraft traffic. See Traffic Conflict below.

Conflict Detection: The discovery of a conflict as a result of a computation and comparison of the predicted flight paths of two or more aircraft for the purpose of determining conflicts. (ICAO)

Conflict Detection Zone (CDZ): Zone used by the system to detect conflicts. The CDZ is defined by the sum of ANSD, position uncertainties, and trajectory uncertainties. By attempting to maintain a measured separation no smaller than the CDZ, the system assures that the actual separation is no smaller than the ANSD.

Conflict Detection Zone (CDZ) Alert: An alert issued at the specified look ahead time prior to CDZ penetration if timely action is not taken. Timely avoidance action is required.

Conflict Detection Zone (CDZ) Penetration Notification: Notification to the crew when the measured separation is less than the specified CDZ.

Conflict Prevention: The act of informing the flight crew of flight path changes that will create conflicts.

Conflict Resolution: A maneuver that removes all predicted conflicts over a specified “look-ahead” horizon. (ICAO -The determination of alternative flight paths, which would be free from conflicts and the selection of one of these flight paths for use.)

Domain: Divisions in the current airspace structure that tie separation standards to the surveillance and automation capabilities available in the ground infrastructure. Generally there are four domains: surface, terminal, en route, and oceanic/remote and uncontrolled. For example, terminal airspace, in most cases comprises airspace within 30 miles and 10,000 feet AGL of airports with a terminal automation system and radar capability. Terminal IFR separation standards are normally 3 miles horizontally and 1000 feet vertically.

Explicit Coordination: – Explicit coordination of resolutions requires that the aircraft involved in a conflict communicate their intentions to each other and (in some strategies) authorize/confirm each other's maneuvers. One example of an explicit coordination technique would be the assignment of a 'master' aircraft, which determines resolutions for other aircraft involved in the conflict. Another is the crosslink used in ACAS.

Generic Conflict: A violation of parameterized minimum separation criteria for adverse weather, aircraft traffic, special use airspace, other airspace, turbulence, noise sensitive areas, terrain and obstacles, etc. There can be different levels or types of conflict based on how the parameters are defined. Criteria can be either geometry-based or time-based.

Implicit Coordination: – Implicitly coordinated resolutions are assured not to conflict with each other because the responses of each pilot are restricted by common rules. A terrestrial example of an implicit coordination rule is “yield to the vehicle on the right.” Implicitly coordinated maneuvers do not require that the aircraft involved in a conflict communicate their intent to each other. Examples in aviation of implicit coordination include VFR flight rules, east/odd, and west/even altitude assignments.

Low Level Alert: An optional alert issued when CDZ penetration is predicted outside of the CDZ alert boundary.

Positional Uncertainty: Positional uncertainty is a measure of the potential inaccuracy of an aircraft’s position-fixing system and, therefore, of ADS-B-based surveillance. Use of the Global Positioning System (GPS) reduces positional inaccuracy to very small values, especially when the system is augmented by either space-based or ground-based subsystems. However, use of GPS as the position-fixing system for ADS-B cannot be assured, and positional accuracy variations must be take into account in the calculation of CDZ and CAZ. When aircraft are in close proximity and are using the same position-fixing system, they may be experiencing similar degrees of uncertainty. In such a case, accuracy of relative positioning between the two aircraft may be considerably better than the absolute positional accuracy of either. If, in the future, the accuracy of relative positioning can be assured to the required level, it may be possible to take credit for the phenomenon in calculation of separation minima. For example, vertical separation uses this principle by using a common barometric altitude datum which is highly accurate only in relative terms.

Regime: Divisions in the future airspace structure in contrast to the current concept of domains. Based on the European concept the three regimes are:

Managed Airspace (MAS)

- Known traffic environment
- Route network 2D/3D and free routing
- Separation responsibility on the ground, but may be delegated to the pilots in defined circumstances

Free Flight Airspace (FFAS) (Also known as Autonomous Airspace)

- Known traffic environment
- Autonomous operations

Separation responsibility in the airUnmanaged Airspace (UMAS)

- Unknown traffic environment
- Rules of the air

See section 1.1.3.

Safe Flight 21: An office in the FAA, which is responsible for exploring, defining, demonstrating, and implementing new technologies designed to improve airspace operations.

State (vector): An aircraft's current horizontal position, vertical position, horizontal velocity, vertical velocity, turn indication, and navigational accuracy and integrity.

Traffic Conflict: Predicted converging of aircraft in space and time, which constitutes a violation of a given set of separation minima. (ICAO)

Trajectory Uncertainty: Trajectory uncertainty is a measure of predictability of the future trajectory of each aircraft. There are a number of factors involved in trajectory predictability. These include knowledge of a valid future trajectory, capability of the aircraft to adhere to that trajectory, system availability (e.g. ability to maintain its intended trajectory with a system failure in a non redundant system vs. a triple redundant system), and others.

User-Preferred Trajectories (UPT): A series of one or more waypoints that the crew has determined to best satisfy their requirements.

Airborne Conflict Management (ACM) Application

This section describes the Airborne Conflict Management Application (ACM). An application overview is given in Section 0. Section 2.2 identifies the phases of flight, processes, and roles associated with the flight operations. The phases, processes, and roles have been identified to aid the thorough consideration of the ACM application safety and performance analyses. Section 2 contains two analyses including: 1) hazards and potential operational consequences for ACM, 2) fault tree analysis for the operational hazards associated with flight using the ACM application. Based upon these analyses and consideration of the most demanding operational scenarios for the ACM application, the performance requirements have been established. Section 3 summarizes the operational requirements for an ACM system in an easy to reference table and includes a list of high level functional requirements.

ACM Application Overview / Abstract

The Airborne Conflict Management (ACM) concept includes detecting conflicts, determination of maneuvers that would create conflicts, and suggesting resolutions to prevent violations of airspace separation criteria against all other properly equipped aircraft/vehicles. A full ACM application requires three separate functions: Conflict Detection (CD), Conflict Prevention (CP), and Conflict Resolution (CR). ACM is a core enabling function for the global implementation of the Free Flight concept, as it will permit pilots to fly user-preferred trajectories while avoiding conflicts with other aircraft.

Potential benefits include safely increased user flexibility and efficiency, increased capacity, global interoperability, operational scalability, reduction of environmental load, and lower infrastructure costs. The ACM CD function will provide alerting and relevant traffic information, if displayed, to help the pilot identify existing conflicts with other aircraft based on current flight states and intents. The ACM CR function will provide suggested resolutions to assist the pilot in preventing these conflicts. The ACM CP function will provide information to assist the pilot in preventing maneuvers which will lead to immediate conflicts. The actions in response to this information, alerts, and resolutions may be coordinated with the air traffic service provider or may be solely managed by the pilot, depending on the operating environment and flight rules in effect at the time.

A CD alert will inform the pilot or flight crew of a predicted loss of separation and enable them to more quickly and accurately identify the aircraft and geometry involved in the conflict, thereby enhancing traffic conflict awareness. Without this alert, the pilot may identify a conflict later in the process, or not at all. With it, both traffic awareness and traffic conflict awareness are enhanced. In this way, CD will mitigate failures that can lead to a loss of separation or collision. The CR part of this application will provide recommended conflict resolutions or guidance cues to assist the pilot in resolving these conflicts. The CP part of this application will predict conflicts that would be created if current ownship flight state or intent is changed in a given manner, and offer guidance cues to prevent maneuvers that will lead to these conflicts.

Currently, ATC separation standards are usually distance-based. These current standards were not explicitly derived from a system level analysis. Instead, they have historically evolved from experience, based on the limited accuracy of the ground surveillance and display systems and vagaries in the controller/radio/pilot control loop. Some procedural separation standards are time based. Future separation standards, based on more accurate and timely position and intent information, may be significantly smaller. ACM is designed to facilitate translation of these capabilities into reduced separations.

The ACM system is built around the concept of two zones: The Conflict Detection Zone (CDZ) and the Collision Avoidance Zone (CAZ). Avoiding CDZ penetration will ensure that legal separation is maintained. For cases where no legal separation standard exists (such as a GA VFR traffic pattern), CDZ alerts will protect either a fixed or a pilot-selectable distance. Initially the pilot or system will change this distance for different phases of flight, or varying operating environments. The CAZ is used to provide collision avoidance in the case of pilot or system failure in maintaining normal separation.

The Conflict Preventions (CP) function of ACM is designed to enable users to avoid creating a conflict where none currently exists. A "potential conflict" is declared and displayed when, if the current trajectory is altered in a given manner, a conflict would be immediately declared. The annunciations may take many forms, including some mix of, but not necessarily limited to, heading, track, airspeed, climb rate, climb angle altitude, turn rate, bank angle, etc., restrictions.

The Conflict Detection (CD) function of ACM is designed to warn users that the ACM system predicts a loss of separation within a given time/distance/probability. There are three CD alerting levels: Low, CDZ and CAZ. The thresholds at which these alerts are declared are based on the following concepts:

An optional Low Level Alert enhances awareness about a developing traffic situation and is issued as early as possible with due consideration given to nuisance alerts.

A required CD Alert, triggered off the CDZ, is issued soon enough to allow the pilot sufficient time to maneuver to avoid loss of separation.

A required CA Alert, triggered off the CAZ, is issued soon enough to avoid a collision, dangerously close spacing and ACAS alerts.

The Collision Resolution (CR) function of ACM is triggered by the CD alerts, and is designed to provide guidance to the crew that will prevent the loss of separation. For the CDZ CR timely avoidance action is required. If a CAZ alert occurs, there has been significant system degradation due to equipment failure, human error, or some other rare but significant factor. In this case, aggressive corrective action is required to prevent a dangerous situation. The CR function is designed to be completely interoperable with, and functionally independent of, existing Airborne Collision Avoidance Systems (ACAS).

1 Airborne Conflict Management (ACM) Application Description

1.1 Introduction

Section 1 of this Appendix presents an application description for Airborne Conflict Management (ACM) using Automatic Dependent Surveillance-Broadcast (ADS-B) and related surveillance sources. The ACM concept includes detecting conflicts, monitoring for potential conflicts, and suggesting resolutions to prevent a violation of airspace separation criteria against all other properly equipped aircraft/vehicles.

1.1.1 Background

ACM is a core enabling function for the global implementation of the Free Flight concept, as it will aid pilots to fly user-preferred trajectories while avoiding conflicts with other aircraft. The long surveillance range afforded by ADS-B will enable alerts to be issued in time to solve the conflicts with minimum disruption to flight path. It is expected that the time provided by this long range will allow for a variety of solutions, or optimized solutions, thus enabling the choice of user-preferred trajectories while avoiding conflicts with other aircraft.

This document describes a fully integrated ACM system in which all three ACM functions, Conflict Detection (CD), Conflict Prevention (CP), and Conflict Resolution (CR), are provided by the system. An ACM system that provides only the CD function is described in Appendix X Section Y. Other combinations of functions may be permitted, but application descriptions have not yet been developed.

The ACM CD function will provide alerting and relevant traffic information to help the pilot identify existing conflicts with other aircraft based on current flight states and intents. The ACM CR function will provide suggested resolutions to assist the pilot in preventing these conflicts. The ACM CP function will provide information to assist the pilot in preventing maneuvers which will lead to immediate conflicts. The actions in response to this information, alerts, and resolutions may be coordinated with the air traffic service provider or may be solely managed by the pilot, depending on the operating environment and flight rules in effect at the time.

It is expected that ultimately there will be a high percentage of equipage in all environments. This would include the various incarnations of ACM, including a CD-only system. For certain operations, such as in autonomous airspace, it is expected that there will be 100% equipage with a full ACM system.

1.1.2 Operational purpose

The ACM application is being developed for use in all phases of flight and all air traffic environments. Advances in navigational accuracy (e.g., through GNSS), new methods of communication among aircraft and with the ground (e.g., ADS-B), and advances in flight deck displays (e.g., Cockpit Display of Traffic Information (CDTI)) will enable new or revised operational practices. These new practices, enabled and underpinned by ACM, will meet or exceed current levels of safety in all anticipated operating environments. Besides safety, other potential benefits include increased user flexibility and efficiency, increased capacity, global interoperability, operational scalability, reduction of the environmental load, and lower infrastructure costs.

ACM will enhance safety by providing a distributed, cooperative, separation assurance system. There will be up to three independent opportunities to achieve situational awareness: observations by the ownship pilot, by the “intruder” pilot, and, if available, by the ground based air traffic team. Each can act to preserve separation, if only by drawing the attention of the person responsible for maintaining it to a potential loss of separation. Currently, in an IFR environment, only the ATSP provides conflict detection and separation assurance. In VFR, pilots use "see and avoid" as the only method to prevent collisions. In mixed IFR/VFR operations, while in VMC, both pilots and controllers share conflict detection and separation assurance responsibilities.

A CD alert will inform the pilot or flight crew of a predicted loss of separation and enable them to more quickly and accurately identify the aircraft and geometry involved in the conflict, thereby enhancing traffic conflict awareness. Without this alert, the pilot may identify a conflict later in the process, or not at all. With it, both traffic awareness, and traffic conflict awareness are enhanced. In this way, CD is intended to mitigate failures that can lead to a loss of separation, which in turn leads to increased chances for a collision.

The CR part of this application will provide recommended conflict resolutions or guidance cues to resolve conflicts detected by the CD function. The CR function is designed to be completely interoperable with and functionally independent of existing Airborne Collision Avoidance Systems (ACAS).

Under normal circumstances, conflicts are expected to be resolved at long range by minor changes to the flight path. However, ACM is also designed with two shorter-range alert thresholds in which increasingly urgent alerts and updated resolutions are provided as necessary for required avoidance maneuvers.

The CP part of this application will predict conflicts that may occur if current flight state or own ship intent is changed. As such, it will offer guidance cues to prevent changes that will lead to conflicts.

In the future, it will be desirable for an ACM system to also take into account known, non-aircraft "threats" (e.g., terrain, weather, and restricted airspace); however, such capabilities are not described in this document.

1.1.2.1 Future goals

In the long term, ACM is expected to provide these operational benefits:

- Provide airborne self-separation capability
- Maintain or enhance current safety levels
- Help enable Free Flight
- Safely increase capacity, efficiency, and flexibility
- Reduce environmental stress per flight

1.1.2.2 Present goals

Currently, procedures do not allow the full benefits that ACM may provide. Even so, ACM may still provide these operational benefits:

- Enhanced general traffic situational awareness
- Enhance airborne traffic conflict awareness
- Provide a robust safety backup to the ATC system
- Maintain or enhance current safety levels with increasing traffic

- Maintain or reduce controller workload and voice communications load with increasing traffic
- Reduce environmental stress per flight

1.1.3 Domain and Regimes

This section first describes an assumed end state where separation standards are variable—based on various dynamic parameters such as position accuracy, integrity, application, and phase of flight. We have adopted the European usage of "regime" to distinguish the new concept from the current concept of "domains", which are based generally on the current Air Traffic Control System work structure such as terminal and en route. The document then describes how the system would work in the present wherein separation standards are a number of fixed values based, in the most part, on air traffic domain, such as 3 miles horizontally and 1000 feet vertically in terminal airspace. Both now and in the future, the system must support automatic or manual adjustment to utilize the appropriate separation standards.

In addition, some applications may determine that the local ACM separation standards, alert zones, etc are incompatible with their requirements. Those applications will send to the ACM application any changes in parameters for specific aircraft including any aircraft that should be ignored by ACM because that application has taken full responsibility for the ACM functions. For instance, a Closely Spaced Parallel Approach Application may direct ACM to reduce the separation standard and alert times for all aircraft on the parallel approach or it could take over separation and backup functions completely and direct ACM to ignore all aircraft on the parallel approach.

1.1.3.1 Airspace Transitions

One of the largest areas of uncertainty involves transitioning from one regime to another – e.g. from autonomous airspace to managed airspace. As discussed later, we expect that in some implementations, system functionality will automatically transition from regime to regime. All systems will be required to have a method for the pilot to manually transition.

Because of these airspace transitions, there may be traffic encounters where the aircraft involved will be in two different regimes. This may occur strictly because of the geometry and position of the aircraft or because one or both aircraft systems did not transition at the same point. Although these encounters should be infrequent, the various interactions between aircraft operating with different regime parameters need to be examined.

1.1.3.2 Future Regimes

From the European perspective, the airspace regimes proposed for future air traffic domains are Unmanaged Airspace (UMAS), Managed Airspace (MAS), and Free Flight Airspace (FFAS). Although the European structure and terminology is not directly applicable to the FAA NAS at this time, it does correspond well to various uses of ACM in all airspace. Therefore, in this document we have adopted UMAS and MAS as the terminology describing their two respective functionalities. However, to avoid confusion with the Free Flight Concept we use the term "Autonomous Airspace" in place of FFAS.

Although three airspace regimes are envisioned for commercial operations, the following sub-levels of airspace and delegation are foreseen:

1.1.3.2.1 Managed Airspace

Managed airspace is very similar to today's controlled airspace except for increased accuracy and integrity through better navigation (such as GPS) and ACM capability. In this environment, the ATSP will maintain control. However, with the added capability as outlined above they have the option to allow aircraft to avoid conflicts by operating without delegation, with delegation and with limited delegation. It may also be possible for ATSP to temporarily assign separation responsibility to an aircraft or a group of aircraft.~~Under all these operating conditions, the separation standards will be controlled by the ATSP. As a result, the descriptions presented in the Present Domains section below reflect the anticipated operational environment.~~

Without delegation—Conflict resolution is defined by the ATSP and communicated to the Flight Crew for execution.

With delegation—Conflict resolution is defined by the flight crew and communicated to the ATSP for approval. Approval is communicated to the Flight Crew prior to execution.

With limited delegation—Conflict resolution is constrained by the ATSP, while the Flight Crew selects the details of maneuvers.

With temporarily assigned separation responsibility—Conflict resolution is defined and executed by the flight crew with no further ATC interaction.

Under all these operating conditions, the separation standards will be controlled by the ATSP. As a result, the descriptions presented in the Present Domains section below reflect the anticipated operational environment.

Various levels of equipage are anticipated.

1.1.3.2.2 Autonomous Airspace

In autonomous airspace, all aircraft will be equipped with an ACM capability and will be capable of self-separation within the specific rules of particular airspace domain. It is anticipated that initially terminal, en route, and oceanic operations may have different separation standards as presently provided in managed airspace. However, the assumed end state will have variable separation standards based on dynamic parameters such as position accuracy and integrity rather than on phase of flight. The ACM system and aircraft operators must be capable of operating/transitioning under the different rules without ATSP direction.

All individual aircraft broadcast position and intent information, including any conflict resolutions. Other users act based on the information. ATSP may provide other services, such as traffic flow management, and airspace transition assistance to managed airspace.

1.1.3.2.3 Unmanaged Airspace

Separation and maneuvering responsibility is delegated to the aircraft, and some aircraft may not be in communication with ATC. Various levels of equipage are anticipated.

1.1.3.3 Present Domains

The ACM application will be used in *all airborne airspace domains, i.e., en route,* terminal, *and oceanic/remote.* The ACM function will be applicable to *any flight operation* conducted under Visual Flight Rules (VFR) and Instrument Flight Rules (IFR), in both IMC and VMC, and among all equipped aircraft types. The aircraft's

ACM system will be designed to work with and without an interface to the ATM system. Usage of the system will be similar to the managed and unmanaged cases specified above. Usage may be limited to providing safety backup information to the ATSP. Various levels of equipage are anticipated.

1.1.3.3.1 Representative Environments

This specific ACM application pertains to enhancing operations under current IFR and VFR regulations. Three environments are specifically addressed throughout this description, being chosen as fairly representative of various challenges. These environments are: GA traffic pattern, terminal area operations, and high altitude en route operations. These environments are described in the following table, and further described in the following paragraphs.

Table 1: Representative Environment Summaries

	GA Traffic Pattern	Radar Terminal Area	High Altitude En route
Lateral Extent	5 SM of airport	30 NM of airport	NAS
Vertical Extent	0-3000’ AGL	0-10,000’ AGL	10,000’-FL500
Met Conditions	VMC	All	All/IMC above FL180
Flight Rules	VFR with IFR arrivals	IFR/VFR	IFR
Radar Coverage	Mixed	Yes	Yes
Towered	Mixed	Yes	N/A

One environment that presents a challenge for ACM is the GA traffic pattern, which includes:

- **High traffic density in selected airports.** Many GA airports have limited flight operations; however, in some cases, GA “reliever” airports far exceed the large scheduled carrier airports in terms of takeoffs and landings.
- **Mixture of aircraft classes.** GA traffic pattern may support operations by virtually every class of aircraft at any given time.
- **Mixture of operations.** The GA traffic pattern environment may simultaneously support IFR arrival and departures flying published routes or ATC vectors, VFR traffic arriving, departing, and remaining in the pattern, and instrument approaches flown under VMC for training or currency.
- **Potential for high pilot workload.** The GA traffic pattern, because of the density of traffic and the mixture of both aircraft and operations, is one that may increase the pilot typical workload.
- **Close proximity during operations.** Aircraft operating in this environment may normally be operating in close proximity to other aircraft. Also, geometric flight relationships, which would otherwise be considered a threat, may be normal in this environment.
- **Closely spaced runways.** Closely spaced, crossing, or both close and crossing runways at some airports create among the most dynamic and challenging conflict awareness situations.
- **Towered and non-towered.** Operations can be either controlled or uncontrolled.

1.1.3.3.2 Terminal Area Operations

Another challenging environment is terminal area operations. While the GA traffic pattern is assumed to be VMC, terminal area operations can be IMC or VMC, IFR or VFR, and also contain a wide variety of aircraft both departing from and arriving at a given field. Highlights of the terminal area, for the purposes of this document include:

- **High traffic density in selected airports.** Many aircraft are climbing or descending to or from the en route structure. Additionally, many non-Class B terminals also include transient aircraft flying point to point, both on and off airways.
- **Mixture of aircraft classes.** Like the GA traffic pattern, the terminal area may support operations by virtually every class of aircraft at any given time.
- **Mixture of operations.** Terminal areas may simultaneously support IFR and VFR climbs, descents, and transits flying published routes or vectors.
- **Potential for high pilot and controller workload.** The terminal area is full of airspace complex transitions and, because of the density of traffic and the mixture of both aircraft and operations, features perhaps the highest pilot workload.
- **Built-in apparent conflicts.** In terminal operation, it is common for aircraft to fly complex flight paths. They fly trajectories that often would, if continued indefinitely, lead to loss of separation. In practice, the next planned change in trajectory occurs before separation is lost.

1.1.3.3.3 High Altitude En Route Operations

A less challenging environment is the high altitude en route structure; however, this environment is where airliners spend the majority of their time and features potentially high closure rates and large separation requirements. See-and-avoid separation techniques are problematical in this environment. Some significant aspects of this environment are:

- **High closure rates.** Head-on traffic can easily close at nearly 1000 Knots in this environment. At such speeds, the pilot is unable to visually acquire the target aircraft or predict its trajectory in time to avoid a loss of separation. For instance, a pilot would have just 30 seconds to prevent a loss of separation (5 NM) on an approaching plane when it is still over 13 miles away.
- **Larger separation criteria.** In non-RVSM airspace, required aircraft separation can be 5NM and 2000 feet. At such distances, it is unlikely that a pilot will be able to accurately determine that a loss of separation has occurred. Even in VMC, such large spacings make it possible for a loss of separation to occur without either aircrew ever seeing the other.
- **More orderly and predictable operations.** All traffic is assumed to be high altitude, operating IFR. In this environment, most aircraft are on fixed or desired routes with minimal tactical maneuvering.
- **Aircraft may have less maneuver capability.** For much of the operation in this environment, aircraft tend to be near their practical service ceilings and less maneuverable than when lower.

- **Low pilot workload.** This is the most benign phase of flight. If there is a problem with crew response in this environment, it may be in relation to inattentiveness due to monotony.

1.1.4 Justification

Potential benefits include safely increased user flexibility and efficiency, increased capacity, global interoperability, operational scalability, reduction of the environmental load, and lower infrastructure costs.

1.1.4.1 Safety

Analysis of U.S. safety data indicate that the majority of the critical near-midair incidents within U.S. airspace occur during transition between different classes of airspace, or when aircraft are not operating under the same flight rules (e.g., VFR aircraft not in radio contact with air traffic control mixed with aircraft on an IFR flight plan and under radar surveillance). Approximately 38% of the near-midair incidents were between aircraft under visual flight rules. In 1999, 17 General Aviation (GA) midair collisions occurred in the United States or, on average, one mid-air collision every third week. Eighty percent of the midair collisions that occurred during “normal” flight activities happened within 10 miles of an airport, and 78 percent of the midair collisions that occurred in the traffic pattern happened at non-towered airports. A review of two years of critical near-midair collision incident report narratives reveals a continuing inability to “see-and-avoid” other aircraft in sufficient time to preclude a critical situation. Analyses of Critical Near-Midair Collisions also indicate that increased situational awareness by the flight crews has the potential to reduce the number of Critical Near-Midair Collisions by over 75 percent.

Aircraft equipped with ADS-B and CDTI will have the capability to broadcast and display aircraft location and intent data to electronically see-and-avoid other aircraft. More than simply displaying traffic, ACM will also alert pilots of developing conflicts and will suggest resolutions to those conflicts. This will increase the pilot’s situational awareness, a key to increased safety. As a result, safety advantages are realized through the increased avionics capabilities based, in large measure, on ADS-B. Additionally, implementation of ACM supports the National Transportation Safety Board (NTSB) recommendation, A-72-157, which calls for the development of a total midair collision avoidance system and proximity warning system that is cost feasible to the general aviation community.

1.1.4.2 Capacity and Efficiency

ACM supports increased user preferences, such as pilot or AOC selected trajectories, and by providing users with expanded situational awareness and greater flexibility in the use of the airspace. User efficiency may be improved by decreasing separation minima and/or associated buffers, while maintaining or increasing the current level of safety. Reducing the need to operate on a specified route structure and/or at fixed altitudes enhances efficiency. Users may also gain efficiency by applying their goals and preferences directly to flight management rather than relying on the ATSP to make assumptions about user preferences.

ACM is an integral element in increasing capacity to meet projected worldwide demand. Under the ACM paradigm, each aircraft that enters a volume of airspace brings additional capabilities in both decision support automation and human decision-making. Higher traffic throughput levels are attainable before system capacity limits are reached. The International Air Transport Association noted, in

May 1999, that delays are reaching a “crisis condition” in Europe. Similarly, the Air Transport Association reported that U.S. air traffic is projected to increase by 54 percent in the next 12 years and the number of “severely congested” airports may rise from 25 to 32 in a decade [0].

ACM systems safely support increased capacity through enabling both Free Flight and collaborative decision-making concepts. These concepts include enhanced safety and increased efficiency through:

- Flying user-preferred trajectories.
- Cutting flight times and fuel consumption.
- Reducing the congestion that a rigid airway system imposes.
- Reducing spacing with the same or increased safety levels.
- Improving airborne situational awareness.
- Achieving common situational awareness for controllers and pilots.
- Removing ATSP workload bottlenecks through efficient task distribution.
- Reducing voice frequency congestion.
- Avoiding the effects of communications misinterpretation.

ACM systems can support increased system capacity by enhancing safety for all equipped users—providing pilots an accurate, reliable, cockpit display of potential and existing conflicts and the means to avoid/resolve them. En route, these enhancements are expected to support preferred/direct/optimal routing, thereby reducing the incidence of traffic conflicts by distributing traffic more evenly through the available airspace than does the current “airways” system. Near runways, the on-board monitoring and alerting of potential/developing conflicts may, in conjunction with other ADSB applications, enable increases in airport capacity by supporting higher approach/departure densities with greater safety.

The ACM application supports maximization of aircraft and airspace efficiency by enabling the pilot and, if applicable, Aeronautical Operational Control (AOC), and Air Traffic Service Provider (ATSP), to corroboratively decide safe, optimum routings.

The current ATC system is disrupted by a significant number of resolution advisories (RAs) from ACAS. The ACM system can reduce the number of RAs and provide conflict resolutions that are significantly less disruptive by:

- Providing long range, user-preferred trajectories for conflict resolution, thus reducing the trajectory disruptions associated with short-range traffic conflicts.
- Decreasing the false alarm rate through increased surveillance accuracy and judicious use of intent information.
- Allowing horizontal and speed maneuvers to resolve conflicts in addition to vertical maneuvers.

1.1.4.3 Infrastructure

A mature *Free Flight* environment in which all aircraft are ACM equipped carries with it the advantages of a distributed system. As such, it will not require the intensive ground infrastructure, capital costs, or maintenance costs that today’s system does. With infrastructure and expenses more evenly distributed among air and ground systems, future modernization and maintenance efforts should be both less expensive and less cumbersome than they are today. If done with foresight, changes can be made more easily than with a ground based system. Operating an ATM system with greater situational awareness than today's should resolve some current controller workload issues. The end result of such a distributed infrastructure will be enhanced safety, greater efficiency, and lower operating costs.

An entire ADS-B based ATM system infrastructure is expected to have a significantly lower acquisition and maintenance cost than radar-based ground systems, while allowing for increases in capacity and efficiency. This approach is being tested with the FAA's Capstone program in Alaska, where ADS-B surveillance is used in some areas where radar coverage does not exist and supplementing radar in an area where radar coverage does exist. ACM is an important part of developing such an ADS-B based global system, since much of the world will have no ground based surveillance. Widespread use of ACM may facilitate a decrease in the growing complexity of the ATC system, thereby lowering acquisition and maintenance cost of the ground based infrastructure.

For aircraft operators, some ACM systems are expected to be more reliable and have lower acquisition costs than current ACAS. The ACM safety benefit may provide users with other cost reductions, including lower insurance premiums for aircraft ownership and operations. These, plus the benefits identified in Section 1.3.2, should make ACM attractive to a wider segment of the aviation community, and encourage full aviation fleet-wide equipage. It is anticipated that service providers could require ACM equipage to obtain access to certain airspace. Where this occurs, those who are not equipped will be limited to less efficient routes.

1.1.4.4 Environmental Impact

Global environmental concerns require minimizing environmental impacts from all modes of transportation, including air transport. The U.S. Government General Accounting Office has identified aircraft emissions, especially carbon dioxide, as a major concern [0]. However, the demand for air travel is rising and aircraft movements are predicted to increase substantially. Minimizing flight times and using optimum descent profiles will reduce the environmental load due to both exhaust emissions and noise. Not only will ACM enable Free Flight, allowing optimized trajectories, but it will also reduce disruptions to that optimized flight plan.

This system is primarily focused on enhancing, not replacing other technologies.

1.1.5 Maturity and User Interest

A significant number of research and development activities have been performed in the area of ACM with the active support of ATSP and users in both the United States and Europe. The actual mechanics and algorithms of ACM for Free Flight have been researched by numerous engineers and scientists for several years. Researchers from NASA, Nationaal Lucht-en Ruimtevaartlaboratorium (NLR), EUROCONTROL, and various private companies have developed and tested a number of approaches. The simulation and R&D activities demonstrate that the approach is feasible and beneficial; however, additional research will be required for effective implementation.

1.2 Operational Concept, Roles, and Procedures

Currently, ATC separation standards are usually distance-based. These current standards were not explicitly derived from a system level analysis. Instead, they have historically evolved from experience, based on the limited accuracy of the ground systems and the controller's ability to discern traffic position. Some procedural separation standards are time based. Future separation standards, based on more accurate and timely position and intent information, may be significantly reduced. ACM is designed to facilitate translation of these capabilities into reduced separations.

1.2.1 General Reference Material

The ACM concept described in RTCA/DO-263, *Application of Airborne Conflict Management: Detection, Prevention, & Resolution.* The three functions (CD, CP, and CR) are built around two zones (CDZ and CAZ) that define legal and safety separation standards within any aircraft pairing.

Note: The concept of the Protected Airspace Zone (PAZ), as used in DO-263, has been refined by defining two new terms, Assured Normal Separation Distance and Conflict Detection Zone.

These zones are defined by a number of parameters. Some of these parameters, such as position uncertainty, are dynamically calculated; others such as Assured Collision Avoidance Distance (ACAD) and Assured Normal Separation Distance (ANSD) are fixed.

1.2.1.1 ACAD and CAZ Zones Support Collision Avoidance

The Assured Collision Avoidance Distance (ACAD) is the minimum assured vertical or horizontal distance allowed between aircraft geometric centers. If this separation is not maintained, a collision or dangerously close spacing will occur. These distances are fixed numbers calculated by risk modeling and initially will be based on ACAS separation distances.

The Collision Avoidance Zone (CAZ) is the system-measured area that is sized just large enough that the actual distance between aircraft is not reduced below the ACAD. The CAZ is defined by the sum of ACAD and position uncertainties (see Figure 1). The CAZ is used to provide collision avoidance in the case of pilot or system failure in maintaining normal separation.

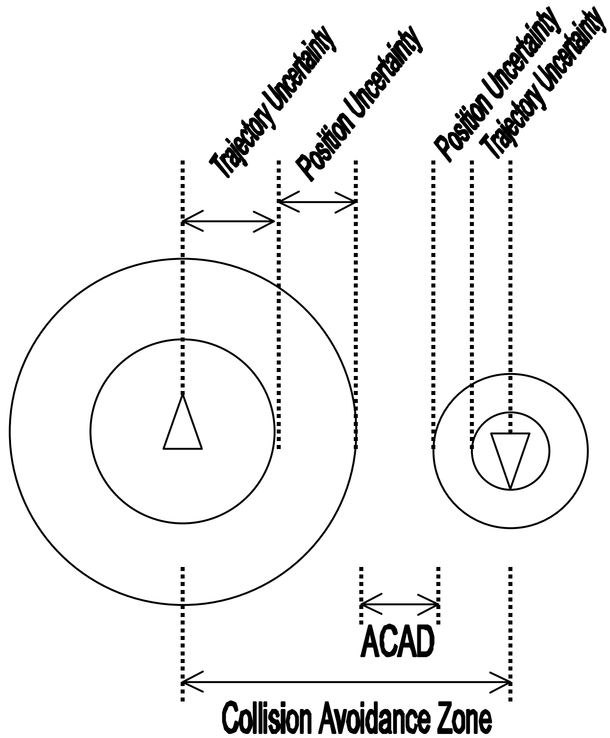


Figure 1: Collision Avoidance Zone

1.2.1.2 ANSD and CDZ Zones Support Conflict Detection

Correspondingly, the ANSD is used in conflict avoidance and is the normal minimum assured vertical or horizontal distance allowed between aircraft geometric centers. These distances are entered by the pilot or set by the system. Initially the ANSD will be based on current separation standards (and will be larger than the ACAD) to prevent ATC alerts. In the long term, collision risk modeling will set the ANSD. Ultimately the ANSD may be reduced toward the value of the ACAD. The Conflict Detection Zone (CDZ) is defined by the sum of ANSD, position uncertainties, and trajectory uncertainties (see figure 2). By attempting to maintain a measured separation no smaller than the CDZ, the system assures that a) the measured separation is no smaller than the sum of the ANSD and the position uncertainties and b) the actual separation is no smaller than the ANSD. For cases where no legal separation standard exists (such as a GA VFR traffic pattern), CDZ alerts will protect either a fixed or a pilot-selectable ANSD. Initially the pilot or system will change the ANSD for different phases of flight, or varying operating environments.

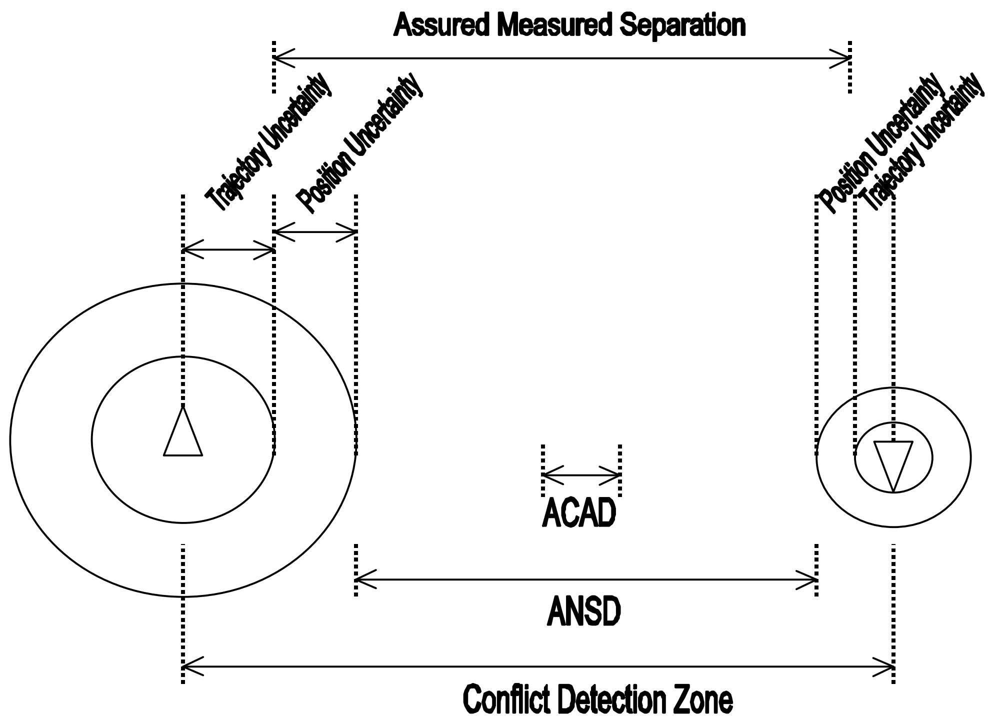


Figure 2: Conflict Detection Zone

1.2.1.3 Position and Trajectory Uncertainties

Positional uncertainty is a measure of the potential inaccuracy of an aircraft's position-fixing system and, therefore, of ADS-B-based surveillance. Use of the Global Positioning System (GPS) reduces positional inaccuracy to very small values, especially when the system is augmented by either space-based or ground-based subsystems. However, use of GPS as the position-fixing system for ADS-B cannot be assured, and positional accuracy variations must be take into account in the calculation of CDZ and CAZ. The sum of ownship and intruder positional inaccuracy is the difference between the measured and actual separations. To assure separation, it is necessary to add the absolute value of the uncertainties to the required separation.

Trajectory uncertainty is a measure of predictability of the future trajectory of each aircraft. Currently the vertical separation is small, in part, due to the predictability of staying at an assigned altitude. If trajectory predictability can be improved in the horizontal dimension, then the separation could be reduced appropriately. There are a number of factors involved in trajectory predictability. These include knowledge of a valid future trajectory, capability of the aircraft to adhere to that trajectory, system availability (e.g. ability to maintain its intended trajectory with a system failure in a non redundant system vs. a triple redundant system), and others.

Both of these uncertainties are present in ownship and intruder aircraft and must be taken into account.

1.2.1.4 Setting Separation Standards for ACM

It is expected that ATC separation standards will be reduced as ground systems are updated to take advantage of the surveillance enhancement provided by ADS-B, thus allowing more accurate determination of traffic position by controllers. The CDZ and ANSD should decrease and/or change shape accordingly and may not be cylindrical. Separation between well-equipped aircraft (e.g. better accuracy, availability, integrity, and continuity) may be smaller than between aircraft with less capable systems. CDZ dimensions will thus become a function of equipage.

Initially, if the system were used by the pilot for a separation task, ANSD size would be set to a value provided by the controller, who retains separation responsibility. The system will add position and trajectory uncertainty to compute the size of the CDZ. This will ensure that the ACM system guides the aircraft to a distance that is compatible with ground radar based system. If the system is only used for backing up the controller, then the ANSD could be set to a distance less than the separation standard to reduce nuisance alarms.

When the controller has the same surveillance source as the ACM system, then both the ground and ACM systems could take advantage of the increased surveillance accuracy and use fixed distance(s) less than the current standards. Both the controller and crew would know that the ACM system was adding a variable surveillance uncertainty component to the distance by which it was avoiding other traffic.

The same would also be true of any other dynamically measured component that could make up part of separation. Some of these components could be encounter geometry, aircraft equipage, the certainty of aircraft intent, etc. A safety analysis would need to show that a separation standard that takes into account these variable distances is acceptable. Analysis would also have to determine if variable separation standards are acceptable to the controller and crew. Again the ground system must have the same information as the ACM system to insure compatibility.

1.2.2 Concept description

This section describes and defines the general components of the ACM system and how the system will be employed in the future Air Traffic Management environment.

The ACM system provides conflict detection, conflict prevention, and conflict resolution functions against all other properly equipped vehicles (or targets). Position and trajectory information is obtained from ADS-B messages, and compared to the position and trajectory of own aircraft. ("Own aircraft" is a terminology for the aircraft on which the ACM system being described is operating.) By comparing the "own" and "target" information, the CD function monitors and can predict violations of separation standards. The long surveillance range and accuracy provided by ADS-B through the use of a GNSS allows these predictions to be made well in advance of any such conflict.

CD is the basic function of an ACM system. While CP and CR functions are not required for all ACM applications, they are included as part of the full ACM application described here.

The CD function provides three alerting levels:

- An optional Low Level Alert designed to enhance awareness about a developing traffic situation and issued as early as possible with due consideration given to nuisance alerts. These alerts may be disabled to further reduce nuisance alerts. These alerts are provided well before the required CDZ alert (below).

- A required CDZ Alert triggered off the CDZ and issued soon enough to allow the pilot sufficient time to maneuver to avoid loss of separation.
- A required CAZ Alert triggered off the CAZ and issued soon enough that a dangerous situation and ACAS alert is avoided.

The CR function provides three corresponding levels of maneuver advisories (MA), which are displayed concurrently with the corresponding CD alerts. At the first level, MAs need not be coordinated. At the two higher levels, implicit or explicit coordination of MAs is required. Aircraft are required to follow predetermined rules for resolving a conflict. The rules dictate which aircraft must maneuver and/or the maneuver degrees of freedom. These MAs provide one or more suggested maneuvers to the pilot to resolve the conflict.

- An optional Low Level MA, which does not require pilot compliance. These MAs are not coordinated, and provide the pilot with the most flexibility in resolving the conflict. These MAs are disabled if the Low Level Alert is disabled.
- A required CDZ MA, which should offer the pilot a selection of maneuvers. These MAs are coordinated with other ACM systems, and pilot compliance is required in a timely manner.
- A required CAZ MA, which will offer the pilot a specific maneuver. This MA is coordinated with other ACM systems, and pilot compliance is required immediately.

The CP function provides two corresponding prevention advisories (PA). These are determined by analyzing possible own-ship maneuvers, and should be displayed as maneuvering limitations. The PAs should prevent the pilot from flying maneuvers which will cause immediate conflicts.

- An optional Low Level PA indicates maneuvers which, if completed, would trigger a Low Level Alert.
- A required CDZ PA indicates maneuvers which, if completed, would immediately trigger a CDZ or CAZ alert. Since either alert is undesirable and would require immediate attention, there is no requirement to provide specific PAs for each.

1.2.2.1 Operation in the end state

1.2.2.1.1 Autonomous Airspace

In autonomous airspace, the system may issue a Low Level Alert when a CDZ penetration is predicted outside of the chosen CDZ Alert boundary. That is, the Low Level Alert may be issued at any time prior to the issuance of a required CDZ alert on that same target. (See Table 2.) In this case, the system will calculate and display at least one resolution, which need not be coordinated. The crew may select and execute a resolution, or monitor the situation without acting. (Note: It may be necessary to "designate" which aircraft is to maneuver to prevent opposing maneuvers that conflict. "Designation" is being researched and may become a future requirement.) The alert is cleared when CDZ penetration is no longer predicted. Low Level Alerts are an optional feature of the ACM system, but could become required for autonomous operations or if designation is determined to be necessary.

At the specified CDZ Alert boundary (see Table 2), the ACM system will issue a CDZ Alert and will offer (implicitly or explicitly coordinated) resolution maneuvers. The crew will then be required to execute a selected maneuver. The alert is cleared when CDZ penetration is no longer predicted. If there is a CDZ penetration, the system will issue a CDZ Penetration Notification. The aircraft should already be in a maximum CDZ Alert Resolution maneuver. This resolution advisory will maximize CAZ clearance and safely exit the CDZ. The crew will continue to execute the resolution maneuver, in order to maintain safety. The alert is cleared when the aircraft exits the CDZ.

If the conflict detection function predicts a penetration of the CAZ within one-minute (exact parameter and value TBD), then the system will issue a CAZ alert which will direct an aggressive, coordinated, resolution maneuver designed to prevent a CAZ penetration. The crew will then execute the maneuver in order to maintain safety.

It is expected that all aircraft in such airspace will be equipped with an ACM system.

1.2.2.1.2 Managed Airspace

If separation responsibility has been temporarily assigned by ATM to an aircraft or a group of aircraft, system operation in Managed Airspace will be identical to Autonomous Airspace for that pair or group of aircraft.

If the controller maintains separation responsibility, pilots are obliged to follow only ATSP issued clearances. Similar to today's operation, the pilot will still have the obligation to execute all maneuvers required to maintain safety. This means immediately following ACAS RAs or ACM-issued CAZ MAs unless the pilot deems them unsafe or has better information. Unlike today, however, the pilots will have much greater awareness of the traffic situation, which may allow them to identify and request a clearance that is both advantageous to the pilot and acceptable to the controller. Pilots will not be allowed to act on that request in Managed Airspace, until the request is granted by the ATSP. The avionics should allow pilots to disable Low Level alerts and Low Level Alert MAs.

The pilot must be aware that there may be other aircraft in the same airspace that are not equipped or participating. The system will not detect or protect against them.

1.2.2.1.3 Unmanaged Airspace

In Unmanaged Airspace, the system operation will again be identical to that of Autonomous Airspace. However, the pilot must be aware that there may be other aircraft in the same airspace that are not equipped or participating. The system will not detect or protect against them.

1.2.2.2 Operation in Current Environments

Usage of the system will be similar to the managed and unmanaged cases specified above. Usage may be limited to providing safety backup information to the ATSP. The pilot must be aware that there may be other aircraft in the same airspace that are not equipped or participating. The system will not detect or protect against them.

1.2.3 Scenarios for initial analysis

The ACM concept needs more research, simulation, testing, and validation in a variety of areas. Nevertheless, significant work has already gone into the concept, and some operational data already exist. Based on these research efforts, experiences, and data, some initial estimates of parameters can be offered.

Using the three environments previously mentioned, Table 2 summarizes starting points for research and implementation. Alerting times are partially based on the following derived from DO-263:

- Assumed pilot response times to CDZ alerts shall be consistent with the requirement to achieve the necessary lateral and/or vertical separation.
- Assumed pilot response times to CAZ alerts shall be consistent with the requirement to avoid a midair collision.
- Alert times are defined as the time the crew must be alerted to prevent an actual penetration of the corresponding zone. They are based on the time required for:
  - Crewmember recognition of the situation
  - Decision on a strategy to resolve the conflict
  - Coordination of any desired action with Air Traffic Control (if required)
  - Input of the desired control changes
  - Change in aircraft state vector that avoids the penetration.

Table 2: Airborne ACM initial parameter estimates

	GA Traffic Pattern	Terminal Area	High Altitude En route
CDZ Horizontal Size	750 feet Default may be changed by pilot	3 NM	5 NM
CDZ Vertical Size	+/-200 feet Default may be changed by pilot	+/-500 feet	+/-600 feet
LL Alerting Parameters	>15 sec*	>90 sec	>120 sec
CDZ Alerting Parameters	15 sec*	90 sec	120 sec
CAZ Horizontal Size	200 feet	1000 feet	2500 feet
CAZ Vertical Size	+/-200 feet	+/-200 feet	+/-300 feet
CAZ Alerting Parameters	15 sec*	60 sec	60 sec
CDZ Alerting Method	Caution	Caution	Caution
CAZ Alerting Method	Warning	Warning	Warning
Required Terminology	No Change	No change	No change

The optional Low Level Alert longer look ahead time will often result in higher alarm rates. In high-density airspace, this could result in undesirably high alarm rates.

**The minimum time required to react might be longer than the maximum time required to reduce nuisance alerts. This would mean there is no useful prediction time. This issue is, therefore, currently undergoing analysis.*

1.2.3.1 Safety Implications

Where it supplements current procedures (e.g. see-and-avoid operations) and equipage (positive control airspace), implementation and use of the ACM functions are expected to result in an increased level of safety relative to that currently achieved in the same airspace. Failure of one or more ACM functions in such environments will result, at worst, in a return to the current level of safety, which is considered acceptable. In other words, in such conditions, the airspace system is not reliant on ACM functions to maintain the target level of safety.

The same will not be true in autonomous operations or in other operations where credit is taken for ACM functions to achieve separation minima lower than those enjoyed today. In such cases, a much more detailed safety analysis of the effects of failure and of failure modes will be required to define functional and technical requirements. These requirements may vary from an environment that can revert to conventional operations and one in which no such reversion is possible. The distributed nature of autonomous ACM provides a higher level of redundancy than a centralized ATM system. Only the failure modes with a global ADS-B or navigation failure will disable the complete system. Most other failure modes, like human error, require more simultaneous failures to become critical than the current centralized ATM system.

1.2.3.2 Security Implications

ACM specific security implications not covered in the general ASA MASPS security section:

- None

1.2.4 Procedures and responsibilities

ACM may be introduced into the AT system with no changes in FARs, separation responsibilities, clearances, etc. Current operations can apply in all cases – the primary difference being that the AT system as a whole will have some redundancy and more distributed awareness than before. However, for the full benefits of ACM and Free Flight to be achieved, changes in procedures, rules, and responsibilities will be required. Incremental changes will enable incremental benefits prior to the end state. Additional description of these requirements is contained the in Requirements section.

1.2.4.1 Air traffic control

1.2.4.1.1 Initial Usage

Awareness of developing conflicts could lead to additional queries to controllers. Conversely, awareness may allow pilots to avoid/resolve minor conflicts that would otherwise require action by ATC.

1.2.4.1.2 End State Usage

Procedures will be developed to allow changes in separation responsibility (either full or limited) in certain airspaces, to set separation requirements for use in the ACM system, and to allow for free flight operations in autonomous airspace.

1.2.4.2 Flight crew

1.2.4.2.1 Initial Usage

In the event of a CAZ alert, it is expected that the pilot will maneuver immediately to avoid a collision. The crew response to Low Level and CDZ alerts varies by regime.

1.2.4.2.1.1 Unmanaged Airspace

As in current operations, the pilot has separation responsibility. There are not expected to be any changes to this in the future. ACM is expected to increase safety between equipped aircraft but the pilot must be aware that all aircraft may not be equipped.

1.2.4.2.1.2 Managed Airspace

The concept in Managed Airspace is cooperative and distributed air traffic management.

Minor maneuvers per FAR 91.181 ("…this section does not prohibit maneuvering the aircraft to pass well clear of other aircraft…") can be initiated without prior ATC permission.

In the event of a CAZ alert, it is expected that the pilot will maneuver immediately to avoid a collision using his/her emergency authority to see and avoid. The pilot should advise ATC of the maneuver as soon as practical.

1.2.4.2.2 End State Usage

Changes in procedures and rules will allow changes in separation standards and separation responsibility. These changes will likely vary based on the operating environment.

1.2.4.2.2.1 With No Change in Separation Responsibility

There are some applications that are enabled by a simple CDTI system and do not require ACM. For example, with positive identification, the pilot may be given a clearance for a visual climb or descent around conflicting traffic as is done today in terminal airspace.

There are various ways the ACM system can be used with no change in separation responsibility. In many cases, the controller would not need to have prior awareness of ACM equipage. As a safety benefit, the pilot could notify the ATSP when receiving a CDZ Alert. As an efficiency benefit, the pilot may also suggest a preferred solution. (For example, a reduction in speed may be preferable to a heading change, a left turn could be better to avoid weather than a right turn.) This will allow those who equip early to receive benefits.

If the controller is aware of ACM equipage, he/she may clear the pilot to carry out specific tasks that will reduce controller workload and frequency congestion. One such task would be passing a certain distance from a specified aircraft using ACM. In some cases, no rule changes will be required. Other more advanced procedures could also be possible. These could include allowing the pilots to solve a conflict while the controller monitors the solution. An example clearance would be "United 123 and TWA 456 pass each other with a minimum of 6 NM, cleared on course when past."

1.2.4.2.2.2 With Limited Change in Separation Responsibility

Assuming separation responsibility concerns can be resolved, eventually, there will be periods when the responsibility is temporarily transferred to the pilot if requested, or if the ATSP offers and the pilot accepts. This task would be initially between two aircraft but could be expanded to multiple aircraft. This responsibility may be for a specified time or to accomplish a specified operation/procedure. In this case, the pilot will maintain separation responsibility until responsibility is transferred back to the ATSP. Until the specified time or specific operation is completed, the pilot cannot transfer responsibility back to the ATSP unless the ATSP agrees. The ATSP may reclaim responsibility at any time.

1.2.4.2.2.3 Autonomous Airspace

In autonomous airspace (likely to evolve first in places such as oceanic and remote area airspace, and in the upper airspace environment over Europe), all aircraft are expected to be equipped with a full ACM system and the pilot would assume separation responsibility using the ACM system.

1.2.4.3 Airline Operations

No change. (N/A)

1.2.4.4 Flight Service Stations and Automated Flight Service Stations

No change. (N/A)

1.2.5 Potential phraseology augmentation

A mature free flight environment will demand additional/different information exchanges compared with current operations. As new domains, tasks, and procedures are developed, coherent, accordant phraseology must be prescribed. This includes voice and datalink communications. A brief list of examples follows:

- ATSP handoffs between airspace domains with different requirements
- Commence/cancel free flight (ATSP and/or flight crews)
- Coordination of mixed conflicts (free flight with non-free flight)
- Identify aircraft as (non) free flight to other a/c and ground
- Negotiation of separation/conflict resolution between flight crews if necessary

Various technologies and automation will provide alerts, mnemonics, and awareness enhancements to both the ground and air participants. Effective communications will provide prudent redundancy for displays and alerts that serve as the primary information source. For instance, it is assumed that a controller's display will distinguish free flight aircraft from non-free flight aircraft. This may be achieved with color, symbology, or other means (the display is the primary data source). This state can be corroborated with additional phraseology during aircraft check-in ("center, flight123 with you at 3-3-0, free flight"). Here communication procedures confirm separation authority information.

An additional medium for communication, data link, will also be utilized as it is considered an enabling technology for free flight. Efficacy of communication should be assessed in both formats. A policy of simply transcribing voice commands in text fails to optimize data link. There already exist examples of this departure. Data link communications are currently utilized in the oceanic environment and have modified traditional voice communication. In voice communication, "9er" is used for clarity. The textual presentation in data link eliminates the need for a suffix. Similarly, there is no need to "spell-out" letters (a-alpha). If new communications are generated efforts should be made to craft a single phraseology that is consistent and succinct for both media.

It is acknowledged that a transition will evolve current operations to a free flight end state. It is also conceded that this operational concept transition may demand interim procedures that become obsolete in the mature environment. Operational needs should be addressed accordingly. Where possible, transitional phraseology should be fashioned with the higher goal in mind

1.2.6 Aircraft separation / spacing criteria

1.2.6.1 Initial Usage

No Change

1.2.6.2 End State Usage

It is anticipated that aircraft separation standards may be significantly reduced by the use of ADS-B and GPS information which will provide greater accuracy and integrity. Specific separation requirements, such as ACAD and ANSD, may be set as absolute separation requirements, with additional separation added to compensate for position and trajectory uncertainties and integrity level.

1.2.7 Sample scenarios

1.2.7.1 GA Scenario 1. Conflict on approach with no visual acquisition.

An ACM-equipped King Air making an approach to an uncontrolled municipal airport descends through a scattered cloud layer. An ADS-B-equipped Cessna 172 flying below the clouds is practicing touch and go landings. The King Air pilot is on the radio to the ATC Center canceling IFR when the Cessna turns onto final, missing the Cessna's position report on the common traffic advisory frequency. The King Air's ACM notifies the pilot of a low-level conflict and the pilot responds by executing a visual go-around and announcing position on CTAF. The Cessna pilot is made aware that the King Air is nearby, but not (any longer) a collision threat. The Cessna continues its approach and lands safely.

1.2.7.2 GA Scenario 2. Conflict during pattern entry.

The pilot of an ADS-B-equipped Mooney Eagle approaches the downwind leg of a busy GA pattern at an uncontrolled airport. In approaching the pattern, the pilot's estimation of the appropriate aim point to merge without creating a conflict is a poor one, and a conflict with an ACM-equipped Cirrus SR22 on the downwind is created. The conflict is a low-level one, and the Cirrus pilot waits to see if the conflict is resolved. As the Mooney gets closer, its pilot realizes that the entry requires adjustment and comes right a few degrees, resolving the conflict and ending the low level alert on the Cirrus.

1.2.7.3 GA Scenario 3. Conflict between missed approach and crossing traffic.

A Piper Warrior is making a mid-field crossing at an uncontrolled airport. A Beechcraft Bonanza on final approach chooses to execute a missed approach due to turbulence from thermals near the end of the runway. As the Bonanza's vertical speed changes from a slow descent to a fast climb, the ACM systems on both aircraft produce CDZ-level alerts and provide conflict resolution instructions. Both pilots follow their MAs and separation is maintained.

1.2.7.4 GA Scenario 4. Misidentification of conflicting aircraft.

(Adapted from John R. Hull, "The 'Mystery' Airplane," AOPA Pilot, November 1999.)

Two pilots were climbing out of San Diego's Montgomery Field in a Piper PA-28-201 on a flight to Imperial, CA. It was a typical late-summer morning, sunny but hazy with visibility of about 10 miles. They were climbing on an easterly heading when ATC advised that there was a twin-engine Aero Commander at their 12 o-clock and three miles, descending toward them. Straining to see through the haze, the pilot notified the controller that they did not have the traffic in sight. They were instructed to discontinue the climb and advise when the target is sighted. A short time later, both pilots acquired the aircraft and advised ATC. The pilots received permission to resume their climb. Before resuming their climb, they checked their CP system and determined that it was unsafe to climb. Shortly thereafter, a second Aero

Commander was suddenly spotted passing at high speed on an opposite heading some distance overhead.

What happened? Both pilots had mistaken a McDonnell Douglas DC-10, eight or nine miles distant, for the Aero Commander at three miles. The ACM system, aware of the true and total traffic situation, did not make the same error and provided appropriate guidance. If not for the guidance the Piper would have climbed into the path of the oncoming aircraft.

1.2.7.5 Terminal Area Scenario 5. Conflict with non-transponder equipped aircraft.

UPS 9802, an ACM equipped Boeing 767 en route from SDF to ANC is being vectored by Anchorage Approach control. A Capstone-equipped Cessna 172 with no transponder has just departed Merrill Field VFR. The Cessna inadvertently maneuvers into the path of the 767 that is on a radar vector downwind. The controller is handing off another aircraft to the tower and does not see the Cessna blunder. The 767 Captain receives a CDZ MA to climb out of the path of the Cessna and prevents a collision.

1.2.7.6 En route Scenario 6. High Speed, Head on conflict, reduced crew vigilance.

Near midnight over the Rocky Mountains, United 1492 is headed easterly to Columbus, Ohio and has just departed FL330 in a cruise climb to FL 370. Meanwhile, United 1578 is headed west to Los Angeles from Dulles, level at FL 350. Both cockpits are darkened, quiet, calm, and on autopilot. When still 30 NM from each other, the two ACM equipped aircraft both receive a CDZ MA alert. Still nearly two minutes from a loss of separation, the crew of 1492 notifies ATC of the alert and requests permission to execute a 10 degree right turn, one of the MA choices. The ARTCC controller confirms an impending potential loss of separation and clears 1492 to execute the turn. The planes uneventfully pass with 6 NM separation at FL 350.

1.2.7.7 Free Flight Scenario 7 Future End State

Early AM - Domestic Airlines sends its proposed departure and arrival times to the FAA Flow Management System. Domestic uses a scheduled departure time of 0750 EDT for its Flight 123 from JFK to LAX. FAA's prediction of dynamic density and airspace loading for the Free Flight routing determines that there are not departure, en route, or arrival restrictions on for those departure, en route, or arrival times.

0700 Domestic’s dispatch center selects a preferred company routing for Flight 123, based upon the anticipated payload, winds, temperatures, in-flight turbulence, and traffic density information. Domestic’s dispatch briefing for the flight crew includes a “heads up” for possible high traffic densities in Indianapolis Center airspace.

0811 While awaiting takeoff clearance crew checks their proposed route for weather and special use airspace conflicts. Immediately before take-off, the flight crew checks the moving map display to assure there are no conflicts with other arriving or departing traffic.

0811+ Upon take-off, the aircraft surveillance transitions from ground surveillance to a triple redundant system; ADS-B aircraft-to-aircraft with data limited to line of sight ranges, ADS to the satellite surveillance system (which includes the entire FMC 4D trajectory), and an independent satellite multilateration position.

Since the aircraft is in high-density airspace, the aircraft is under ATM control. The controller instructs Flight 123 to execute a 5 degree turn to avoid an arriving aircraft. The controller then authorizes the flight to proceed to LAX via a Free Flight selected trajectory. The Conflict Prevention function of the ACM system shows that the 5 degree turn to avoid the arriving traffic is no longer required. The crew accepts the clearance and allows the cockpit automation to follow the AOC preferred route. The primary means of separation at this point is ACM.

1110 Another aircraft appears in the vicinity of Flight 123, and ACM indicates a conflict. Flight 123's ACM system issues a low-level alert. The pilot decides that the most economical resolution is for 123 to climb to FL 352 slightly ahead of its cruise climb schedule. Shortly thereafter, the other aircraft's CP system indicates that the aircraft should not climb if a conflict is to be avoided. Once at FL 352, Flight 123's CP system indicates that they should not descend or a conflict will occur.

1145 An aircraft approaching the vicinity of Flight 123 has an ACM failure. At this point, the other aircraft is no longer eligible for Free Flight, and the crew notifies ATC of the problem. The Air Traffic Manager now has responsibility to keep that aircraft conflict free of all other aircraft and gives priority to all Free Flight aircraft.

1205 Domestic dispatch contacts the crew to discuss the continuing advisory for low ceilings and fog at LAX. All arriving aircraft are expected to maintain minimum IFR separation standards. There are few unequipped aircraft and the airspace density is low enough to allow Free Flight operations all the way to landing, allowing LAX to continue to operate at near visual rates.

1300 Flight 123 crew uses the CDTI on short final to monitor separation with other aircraft landing on a nearby parallel runway. Flight 123 lands and monitors their cockpit airport surface situational display moving map of LAX as they progress on the surface movement area.

1305 Flight 123 arrives at the assigned gate at the planned time.

1.3 Requirements

The following sub-sections individually address general ACM requirements, followed by requirements for the three major components of a total ACM system. As much as possible, all the following requirements are functional in nature.

1.3.1 General ACM Requirements

1.3.1.1 Display and Interface / Functional

1.3.1.1.1 Functional Requirements

The ACM system shall accept input from other applications, such as Closely Spaced Parallel Approaches, that may direct ACM to either turn off CD and CP or set the size of the CDZ to a specified size for specified target(s).

In the end state, CAZ and CDZ and their corresponding alert thresholds are expected to be predictable and changes should be automated. However, the ACM function shall provide a means for the pilot to manually select the various CAZ and CDZ for exceptions and as a backup function. The ACM function may be integrated with airplane systems to provide these automatic means to transition to the various LL, CDZ, and CAZ values.

In the operational concept transition, these volumes and corresponding thresholds change as a function of the phase of flight. The system must therefore provide a means for the pilot to manually select these values in order to be compatible with ATC separation requirements. See Table 2 for suggested parameters.

The sequence of alerts and their associated levels for the flight crew is generally expected to be the following, but some alerts may be bypassed by system logic:

a) Low level Alert: Optional and Advisory

b) CDZ alert (predicted LOS): Caution

c) CAZ alert: Warning

Note: Level of alerts need to be verified by safety analysis.

While flying certain normal, non-normal, or emergency procedures, the ability to perform a CR maneuver may be limited. Therefore, these conditions have to be broadcast on ADS-B, and responsibility for CR may rest with the other aircraft.

1.3.1.1.2 Display Requirements

If the nature of the maneuver changes during a conflict resolution notification, then an aural and visual alert is required to notify the crew of that change.

If more than one conflict resolution is required to solve all conflicts in a multi-conflict encounter, then only one resolution shall be presented to the crew at a time. The most critical resolution shall be presented first.

If multiple alerts are depicted, then the alerts shall be depicted in such a way as to make it clear to the pilot how many alerts are present.

For any given conflict, there shall be no aural alert of conflict alert termination until all alert levels are cleared for that conflict.

If a CAZ alert is triggered while a CDZ alert is active for the same aircraft, then the CDZ alert shall be suppressed.

The CAZ alert shall be a unique aural and visual.

If the pilot transitions out of a CAZ alert and into a CDZ alert, then a visual change should occur to notify the pilot that a CDZ alert still exists.

An actual loss of CDZ separation may be annunciated. This may be an advisory alert provided the pilot was given a prior caution level alert when the loss of separation was predicted.

For Multi-function displays the CDTI MOPS applies.

Targets for which ACM does not work (e.g. targets with no altitude data) must be indicated.

Any detected failure of the ACM system or its sub-functions must be appropriately annunciated and the crew must be informed of which function(s), if any, are still available. This is considered an advisory/caution level alert.

1.3.1.2 Infrastructure Requirements

1.3.1.2.1 Ground ATC Requirements

1.3.1.2.1.1 Autonomous and Unmanaged Airspace Regimes

ACM in autonomous and unmanaged airspace requires no ground-based infrastructure. However, if ground infrastructure is available, then operations may make use of it.

1.3.1.2.1.2 Managed Airspace

No ACM-specific equipment is required. Even without ground-based ACM equipment, the AT system can benefit from increased aircrew situational awareness and a minor reduction in conflicts as pilots make incremental adjustments (while remaining in compliance with ATC directives) to course or speed in order to ease or resolve conflicts. Another positive impact will be that airborne Conflict Prevention functionality should reduce the incidence of requests for clearances that would result in conflicts.

Obtaining substantial operational benefits will require changes to procedures and/or equipment to support delegation of resolutions to ACM-equipped aircraft. The most important change is allowing controllers to identify which aircraft are ACM equipped. In addition, to ensure interoperability, integration of ACM with ground automation systems may be beneficial.

No additional communications equipment is required.

No additional information from ground to air is required; however, any other high quality traffic surveillance information provided to the aircraft could increase this application's efficacy.

The following requirements are specified for the end state:

- Many of the long term benefits of ACM result from lower separation standards. Lower separation standards will require the integration of ADS-B surveillance information into the ground ATM system for compatibility.
- Decision support tools need to be compatible with the ACM function.
- No additional weather sensing or forecasting equipment required; however, future systems that integrate weather and airspace surveillance with traffic surveillance could increase this application's efficacy.

1.3.1.2.2 Flight Deck/Aircraft

Equipment requirements and interfaces:

- The ACM function may be integrated with an MFD that can display CDTI functionality.
- The ACM system requires the support of attention-focusing alerting (speakers, flashing lights, etc.)

Navigation, communication, and surveillance requirements:

- The ACM function will require an ownship navigation system capable of determining present position, current track, current ground speed, estimated position accuracy, and system health to provide the required level of ADS-B capability.

- This description of ACM requires surveillance of the intruder to include present position, current track, current ground speed, estimated position accuracy, and system health provided by ADS-B, TIS-B or other surveillance sources.
- Navigation and surveillance requirements will be determined from nuisance and missed alarm rate analysis. The navigation and surveillance accuracy will have to be added to the required zone sizes as part of that analysis and thus affects the two rates.
- For the end state, integrity and availability of the system shall be sufficient to support self-separation to defined minima.
- No additional Communication requirements.

1.3.1.2.3 Airline Operations Control Center & Automated Flight Service Stations

No additional equipment requirements and interfaces for the AOC & AFSS.

1.3.2 Conflict Prevention Requirements

The CP portion of ACM is designed to enable users to avoid creating a conflict where none currently exists. A "potential conflict" is declared and displayed when, if the current trajectory is altered in a given manner, a conflict would be immediately declared. The annunciations may take many forms, including some mix of, but not necessarily limited to, heading, track, airspeed, climb rate, climb angle altitude, turn rate, bank angle, etc restrictions.

CP alerting *thresholds* correspond to the CD Alerting thresholds as follows:

- Low-level Conflict Prevention Alerts inform flight crews of maneuvers, which, if executed, would generate LL CD alerts.
- CDZ Conflict Prevention Alerts inform flight crews of maneuvers, which, if executed, would generate CDZ alerts.

1.3.2.1 Display & Interface / Functional

1.3.2.1.1 Functional Requirements

The following rates for the system need to be determined by safety analysis:

- Nuisance depiction/alert rates
- Missed prediction rates
- False depiction/alert rates
- The rate of display of hazardously misleading CP information

1.3.2.1.2 Display Requirements

- A potential conflict of "sufficient interest" must be displayed in some manner to the pilot.
- Annunciating a Low Level prevention advisory is optional and, if implemented, needs to be distinct from CDZ prevention advisories.
- Annunciating a CDZ prevention advisory is required (in a full ACM system).
- Potential conflicts may be further annunciated in a manner that calls the pilots' attention to the situation.

- The ownship pilot must be informed of the maneuvers that would create a conflict.
- Areas that are indicated as potential conflicts but can be transited safely need to be distinguishable from those that cannot (e.g. a range of headings that would cause an MA to be issued if the turn was stopped but can be safely turned through on the way to a conflict-free heading)
- The depiction of Conflict Prevention functions should be clearly distinguishable from Conflict Detection and Conflict Resolution functions.
- The depiction of Conflict Prevention functions should be clearly distinguishable from the actual flight path information for the aircraft (e.g., the depiction of a trial plan used for conflict prevention analysis should be distinguished from the actual aircraft state).
- Conflict Prevention functions should be depicted to the pilot in such a way as to not detract from the Conflict Detection and Conflict Resolution functions.

1.3.2.2 Infrastructure Requirements

1.3.2.2.1 Ground ATC

There are no CP-specific ground ATC requirements.

1.3.2.2.2 Flight Deck

Equipment requirements and interfaces on the flight deck:

- Some form of pilot input may be required to select maneuver ranges which will generate CP warnings, or to enter specific course changes for analysis by the CP logic.
- Otherwise, CP requires no additional hardware, unique (from ACM in general) equipment or interfaces on the flight deck.

Navigation, communication, and surveillance requirements:

- CP requires no additional, unique (from ACM in general) navigation, communications, or surveillance capabilities.

1.3.3 Conflict Detection Requirements

The CD portion of ACM is designed to warn users that the ACM system predicts a loss of separation within a given time/distance/probability. As described previously, there are three CD alerting levels: Low, CDZ and CAZ. The thresholds at which these alerts are declared are based on the following concepts:

- An optional Low Level Alert enhances awareness about a developing traffic situation and is issued as early as possible with due consideration given to nuisance alerts.
- A required CDZ Alert, triggered off the CDZ, is issued soon enough to allow the pilot sufficient time to maneuver to avoid loss of separation.
- A required CAZ Alert, triggered off the CAZ, is issued soon enough to avoid a collision, dangerously close spacing and ACAS alerts.

1.3.3.1 Display and Interface / Functional

1.3.3.1.1 Functional Requirements

Conflict alerts shall be annunciated to the flight crew as soon as a) the confidence of the conflict prediction exceeds the appropriate threshold value and b) time to conflict is less than or equal to an appropriate threshold value.

1.3.3.1.1.1 Confidence Threshold

The appropriate confidence threshold is a function of the desired nuisance/missed alarm ratio (i.e. the probability that the CDZ/CAZ will actually be violated) and possibly also a function of the time to conflict. The function of the confidence threshold is to minimize nuisance alerts such as might be created by transient or maneuvering targets at distance. The specific implementation (e.g. track assessment, probability calculation, etc.) is determined by the vendor.

1.3.3.1.1.2 Time Thresholds

The three CD alerts must be annunciated soon enough to allow the crew to resolve the conflict without penetrating the associated zone. This time threshold includes time periods associated with:

- Crewmember recognition of the situation (on order of response time to ACAS RA for CAZ alert and somewhat longer for CDZ alert)
- Decision on a strategy to resolve the conflict if more than one resolution is provided. (Only one resolution strategy is ever presented for CAZ alerts.)
- Coordination of any desired action with Air Traffic Control (if required; never required for CAZ alert)
- Input of the desired control changes
- Change in aircraft state vector that avoids the penetration
- The minimum time threshold must be at least 15 seconds (TBD) greater than the ACAS RA threshold at the same altitude.

Note #1: Vendors may choose a fixed time which is sufficient for all conditions or may choose to implement logic which makes the time threshold a function of conflict geometry and aircraft performance limits.

Note #2: The thresholds are nominal values; in some situations (e.g. nearby traffic maneuvers to create a “pop-up” conflict) the time available to resolve will be less than the nominal threshold value.

1.3.3.1.2 Display Requirements

Targets that are in conflict with ownship shall be distinguishable from other targets.

Some measure of time to the conflict or urgency of the conflict must be indicated.

Other information such as the location of the conflict may be displayed.

1.3.3.2 Infrastructure Requirements

1.3.3.2.1 Ground ATC

There are no CD-specific ground ATC requirements.

1.3.3.2.2 Flight Deck

Equipment requirements and interfaces on the flight deck:

- CD requires no additional, unique (from ACM in general) equipment or interfaces on the flight deck.

Navigation, communication, and surveillance requirements:

- Surveillance data (e.g. ADS-B) shall support generation of CDZ alerts that can comply with the nominal alert time as defined in 1.3.3.1.1.2 Time Thresholds.
- Surveillance data (e.g. ADS-B) shall support generation of CAZ alerts that can comply with the nominal alert time as defined in 1.3.3.1.1.2 Time Thresholds.

1.3.4 Conflict Resolution Requirements

1.3.4.1 Display & Interface / Functional

1.3.4.1.1 Display requirements

The ownship pilot will be informed of the intruder's relative position, states predicted to result in a loss of separation (that is, those states causing the CDZ and/or CAZ alerts), and states which will maintain separation (that is, states that will resolve the conflict).

The displayed MA shall be discernible from the active flight path or speed cueing of the aircraft.

The depiction of LL MAs should be automatically displayable to the pilot. The pilot should be provided with a means to prevent automatic display of LL MAs.

1.3.4.1.2 Functional requirements

- For CDZ and LL conflicts, the CR function will provide “ownship” with at least one conflict resolution strategy.
- Due to the necessity for prompt action in CAZ conflicts, the CR function will provide “ownship” with only one conflict resolution strategy.
- The CR function shall continue to monitor the situation and update the MAs as necessary. The system shall continue to display MAs until the conflict is resolved. The MAs required to resolve conflicts may need to be updated for several reasons, such as delays in responding, inappropriate response, or changing encounter dynamics. Several methods of presenting MAs exist.
- The Conflict Resolution Systems shall:
  - support MAs involving lateral maneuvers, such as heading and/or flight path and intent changes;
  - support MAs involving vertical maneuvers such as rate, angle, and/or flight path and intent changes;
  - be coordinated with any prior level alerts/resolutions;
  - implicitly or explicitly coordinate CDZ and CAZ MAs.
- In general, if the vendor/user desires, conflict resolution systems *may*:
  - support speed-only maneuvers;

- support combined maneuvers, such as vertical & lateral maneuvers, lateral & speed maneuvers, vertical & lateral & speed maneuvers, etc.
- All conflict resolution strategies shall be adequate to resolve the conflict by themselves. That is, resolution of the conflict shall not depend on the "intruder" cooperatively maneuvering.
- All conflict resolution strategies must take into account aircraft performance limitations, i.e., should not direct a climb MA when at the service ceiling of that the aircraft. In addition to not requiring a maneuver that exceeds the performance capability of the aircraft, maneuvers shall be limited to the appropriate maximum magnitudes later in this section.
- The system must have a mechanism that takes into account terrain, or a method for inhibiting descending MAs.
- CDZ and CAZ Conflict resolutions on different aircraft shall be chosen to avoid incompatible resolution strategies. It is expected that this will be accomplished through CR designs, which include an implicit coordination algorithm.
- Conflict Resolutions shall be calculated taking into account the expected delays of the flight crew in implementing the CR maneuver. Sources of these delays include time for the pilot to analyze and respond to the alert and time for the pilot to implement his response. It is expected that these delays will be smaller for CAZ alerts than for CDZ or low-level alerts because of the higher level of alert and because the pilot will hand-fly the CAZ resolution maneuver. Total delay will likely be on the order of (TBD) seconds for CDZ and LL alerts and 5 seconds for a CAZ alert.
- Pilot must be notified if s/he has targets for which CR cannot or does not work.

1.3.4.1.2.1 LL Alert specific requirements

- The optional LL CR may be acted upon by the crew for more efficient or preferred resolution of a conflict at any time prior to a CDZ CR. There is no urgency to resolve a LL CR. The LL CR may be integrated into the flight management system, flight director system, autopilot system, or other systems to reduce pilot workload and reduce the possibility of pilot error.
- A low level alert is considered an advisory alert. A CR may be offered for maximum efficiency

1.3.4.1.2.2 CDZ Alert specific requirements

- The CDZ CR is designed to be flown within the limits of authority of the autopilot but can be flown manually. Integration into the flight director system and/or autopilot system can reduce workload and the possibility of pilot errors compared to manual input.
- CDZ MAs will advise the pilot how to avoid an imminent penetration of the CDZ. These resolutions could be in the form of "no-fly" zones, "fly" zones, or directions for a specific maneuver. CDZ MAs are expected to be

reasonable, efficient maneuvers requiring nominal changes in heading, rate of climb/descent, and/or speed that can be accomplished using the autopilot. CDZ MAs are coordinated with other ACM systems, which will likely limit the range of solutions available for pilot preference.

- Initial estimates of the maximum magnitudes from level flight for CDZ MA maneuvers are:
- 1,500 fpm vertical rate,
- 25 degree bank turn,
- maximum airspeed changes up to aircraft performance limits.
- If not already maneuvering at these maximum magnitudes, the aircraft must be directed to fly at these maximum magnitudes if the CDZ is ever actually violated, with the goals of not creating an CAZ conflict and exiting the CDZ as quickly as possible.

1.3.4.1.2.3 CAZ MA specific requirements

- The CAZ CR is designed to be flown manually. Integration into the flight director, if the flight director is capable of directing a maneuver at the appropriate level of aggressiveness, can reduce the possibility of pilot error.
- CAZ Alert Resolutions will advise the pilot how to quickly avoid an imminent penetration of the CAZ. When this level has been reached, there has been significant system degradation due to equipment failure, human error, or some other rare but significant factor. Aggressive corrective action is required to prevent a dangerous situation. CAZ MAs are coordinated with other ACM systems, and have a shorter time to complete. As such, this will further limit the range of solutions available for pilot preference.
- Initial estimates of the maximum magnitudes from level flight for CAZ MA maneuvers are:
- 2,500 fpm vertical rate,
- 35 degree bank turn,
- or less if limited by aircraft performance,
- speed changes will likely not be effective and are not expected to be used.
- CAZ resolutions shall avoid penetration of the CAZ and should avoid causing any injuries due to the avoidance maneuver. A CAZ Conflict is defined to be resolved when CAZ penetration is no longer predicted. However, a CDZ Alert and CDZ MA could still be in force.

1.3.4.2 Infrastructure Requirements

1.3.4.2.1 Ground ATC

There are no CR-specific ground ATC requirements.

1.3.4.2.2 Flight Deck

- The CR function may be integrated into an MFD.
- When a conflict is detected, the pilot must be presented with the information required to allow resolution of the conflict. In general, the information

should be made available without pilot action, but in installations where the CD and/or CR functions are shared with other display modes (e.g. on a multi-function display), it would be acceptable for the pilot to be prompted quickly to select the display mode that allows assessment of the conflict and, where necessary, performance of the resolution maneuver.

1.3.4.2.2.1 Equipment requirements and interfaces on the flight deck

- CDTI and associated controls
- Supports attention-focusing alerting (Speakers, flashing lights, electro-shock, etc.)
- Surface for depiction of CR

1.3.4.2.2.2 Navigation, communication, and surveillance requirements

- Navigation and surveillance requirements will be determined from nuisance and missed alarm rate analysis. The navigation and surveillance accuracy will have to be added to the required zone sizes as part of that analysis and thus affects the two rates.
- No additional communication requirements

1.3.4.2.3 ACAS Integration

1.3.4.2.3.1 On Ownship:

If ownship has an ACAS system onboard, ACAS RAs will take precedence over any ACM alerts and resolutions. To prevent the possibility of conflicting advisories, the ACM system must monitor ACAS for any RAs. ACM will not generate any resolutions or guidance that conflicts with the ACAS RA.

1.3.4.2.3.2 Between Aircraft:

In a conflict situation, the extended thresholds of both the CDZ and CAZ MAs (compared to ACAS RA thresholds) should allow the conflict to be resolved without triggering any ACAS advisories. However, it is expected that improved position and velocity information from ADS-B will prevent the ACM system from misidentifying many encounters as conflicts. ACAS may still issue RAs in these encounters. It is possible that measurement differences between ACM and ACAS surveillance techniques, or other problems, may allow ACM and ACAS advisories to exist simultaneously.

Since the ADS-B message set will include the broadcast of the status of any installed ACAS and information on any RAs in progress,[1] the ACM will use this information to avoid any conflicting MAs. Any time ACM detects that another aircraft is issuing a RA, ACM will either inhibit vertical MAs against that aircraft, or, if an ACM vertical MA is in progress, will make no changes to that vertical maneuver.

1.3.4.2.4 Airline Operations Control Center & (Automated) Flight Service Stations (if applicable)

Equipment requirements and interfaces for the AOC & FSS:

[1] approved by SC-186 but not yet included in MASPS or MOPS

- Changes to flight plan will be transmitted to AOC or equivalent services

1.4 Other Considerations

1.4.1 Relationship to other programs and future enhancements

Other programs / efforts that may be considering or related to the application that have not been previously discussed:

- Surface conflict detection
- Crossing runway airborne and surface conflict detection including Land and Hold Short Operations (LAHSO)/Simultaneous Intersecting Runway Operations (SIRO)
- Airspace transitions between phases of flight (en route – terminal – pattern – ground)
- Any future versions of ACAS
- Other applications that will / may be in effect at the same time
- FAROA (Final Approach and Runway Occupancy Awareness)
- Terrain and obstacle applications
- ACAS/TCAS
- Terminal area apps such as closely spaced parallel approaches

1.4.2 Training requirements

- The crew must be trained in the use and operation of the system.
- The crew must understand that only conflicts with suitably equipped targets will be detected; they must remain as vigilant as ever for conflicts.
- Pilot procedures during ACM operations should conform to CRM principles. Therefore, the PF and PNF are expected to work together and share information as appropriate to the development of optimum procedures to ensure situational awareness and safety.

1.4.3 Other issues

- None

1.5 References

Aviation and the Environment: Aviation's Effects on the Global Atmosphere Are Potentially Significant and Expected to Grow, GAO/RCED-00-57, February 18, 2000

Phillips, Don, 21 Days, 18 Flights, The Washington Post, June 13, 1999

2 Analysis of Surveillance Requirements to Support ACM

2.1 Performance Requirements Rationale Overview

By defining the Airborne Conflict Management (ACM) phases and processes and performing hazard and safety analysis, fault tree analysis, and ACM modeling and Monte Carlo analysis, minimum performance requirements are determined. ACM is intended to work with whatever navigation information is available, but to assure safety, integrity bounds must be known. ACM is intended to work in all airspace, and GPS augmentation (WAAS or LAAS), while useable by ACM when available, is not required for ACM. Barometric altimetry with integrity is required for vertical separation.

Where possible, ACM requirements are based on parameters defined by the ADS-B MASPS. Minimum requirements for Navigation Accuracy Category-Position (NAC_p), Navigation Accuracy Category-Velocity (NAC_v), Navigation Integrity Category (NIC), and Surveillance Integrity Level (SIL) are established. One or more of the Barometric Altitude Quality (BAQ) codes will be defined to set vertical error bounds with integrity.

Minimum ACM requirements are also imposed on the ADS-B update rate, ADS-B coverage range, and the range corresponding to 95% probability of reception.

2.2 Airborne Conflict Management: Phases and Processes

The ACM application is expected to operate in all phases of flight and under all air traffic environments. The activities involved in using ACM vary with the air traffic environment.

There are 3 different operational environments that are considered – autonomous airspace, managed airspace, and unmanaged airspace.

Because ACM operation in autonomous airspace is similar to ACM operation in unmanaged airspace, they are described together. ACM operation in managed airspace is described separately.

Although aircraft intent information may be useful in some circumstances, intent is not required for ACM. This analysis does not include the use of aircraft intent information.

2.2.1 ACM in Autonomous/Unmanaged Airspace

There are four distinct phases for the ACM application in autonomous/unmanaged airspace:

- P1. ACM startup
- P2. ACM setup
- P3. Conduct flight with active ACM
- P4. Complete ACM assisted flight

These phases are illustrated in Figure 3 below along with the specific roles of the flight crew, air traffic control, and the ACM equipment. Autonomous and unmanaged airspace are treated together; differences would be handled procedurally, particularly with respect to the involvement of ATC. For example, in some situations involving unmanaged airspace, the steps related to ATC coordination would not be applicable and would be replaced with appropriate procedural rules.

~~In autonomous/unmanaged airspace, the term ACM assisted flight is used when ACM is providing the primary means of separation.~~

As ACM is assumed to be in use throughout the length of the flight, there are two different ways that an aircraft can enter a particular air traffic environment. Prior to entry into a particular airspace, when the ACM equipment is off (most probably the aircraft is on the ground), activities in Phase 1 need to be completed. However, in most cases the ACM equipment will already be in use, in which case Phase 1 of the operation is skipped and we can directly consider Phase 2.

Phase 3 describes the activities taking place in flight with ACM as a primary conflict management tool and Phase 4 describes the hand over of separation responsibility back to ATC. In autonomous/unmanaged airspace, ACM assisted flight is the term used when ACM is providing the primary means of separation.

Each phase is further subdivided into processes as shown in Figure 4. A large rectangular block depicts each phase; the smaller rectangular blocks represent the processes of each phase. The processes are considered "atomic" in that examination of failures of the processes is sufficient to guarantee the safety of the operation. Many processes occur in parallel as shown by the dividing dotted line.

Phase 1 involves the crew switching on the equipment, which leads to a self startup test run by the ACM equipment. If the test fails then ACM is not operational and the crew reverts to standard procedure. If the test passes then the next phase of operation begins.

In Phase 2 the crew requests and receives clearance to enter autonomous/unmanaged airspace, along with the specific Assured Normal Separation Distance (ANSD) value to be used by the ACM for separation assurance. In P2.3 this ANSD value is entered into the ACM equipment and the flight is ready to enter the autonomous/unmanaged airspace.

In Phase 3 the flight crew relies on ACM to provide separation assurance. In P3.1 ACM monitors for traffic. This process continues in the background throughout this phase.

There are two parts to the ACM: providing conflict prevention (CP) to avoid future conflicts, and providing conflict detection and resolution (CD&R). If an aircraft is detected then both these components act in parallel. For the CD&R function a conflict analysis is first undertaken (P3.3). If there is a conflict, the severity of the conflict is analyzed and one of the three possible alerts – low level, CDZ, or CAZ – is provided, along with resolution maneuver advisories. For low level and CDZ alerts, a choice of maneuver advisories may be provided. For CAZ only one maneuver is provided, and it must be coordinated with other traffic and -flown immediately. The CP function analyzes own-ship course changes that may cause conflicts (P3.10) and appropriate advisories are displayed to the crew. Note that the low level alerting for both functions may not be available in the system or may be switched off by the crew. These processes are followed repeatedly throughout the duration of flight in autonomous/unmanaged airspace.

As the flight reaches the point where autonomous/unmanaged airspace is about to end, separation responsibility is transferred to ATC. This is done through processes P4.1 and P4.2 in phase 4.

2.2.2 ACM in managed airspace

Flight with ACM in managed airspace differs from flight in autonomous/unmanaged airspace. In managed airspace separation responsibility always rests with air traffic control. In a managed environment ACM acts as an advisory tool.

The analysis includes the use of ACM in a managed airspace environment that allows delegation of separation responsibility; that is, even though separation responsibility rests with ATC, the flight crew can specify the conflict resolution based on ACM and fly a chosen maneuver upon approval from ATC.

The application description (section 1.2.2.1.2) describes autonomous use of ACM in managed airspace with separation responsibility temporarily assigned to the flight crew by ATC. This analysis does not specifically address the autonomous use of ACM in managed airspace.

For ACM application in managed airspace there are 3 distinct phases as shown in Figure 5:

P1. ACM startup

P2. ACM setup

P3. Conduct flight with active ACM

Both phases 1 and 2 are unchanged from those for autonomous/unmanaged airspace.

Phase 3 is slightly different from the one in autonomous airspace, as here the separation responsibility still rests with ATC. Though ACM functions remain the same, the crew must get authorization from ATC before carrying out the chosen maneuver (as shown in P3.8 and P3.9). ATC authorization is not required to respond to a CAZ alert, as it is considered an emergency situation. ATC must be informed of the maneuver as soon as practicable (P3.13).

In managed airspace with delegation, conflict resolution is selected by the flight crew with ACM guidance, and communicated to ATC. ACM assisted flight is the term used when ACM is monitoring separation and providing separation guidance. The flight crew must obtain ATC approval prior to executing LL and CDZ maneuvers.

For autonomous use of ACM in managed airspace with separation responsibility temporarily assigned to the flight crew by ATC, there would be no requirement to obtain ATC authorization before maneuvering (P3.8 and P3.9 would be unnecessary.).

Another major change from autonomous/unmanaged airspace is that here there is no fourth phase. This is because ATC maintains separation responsibility.

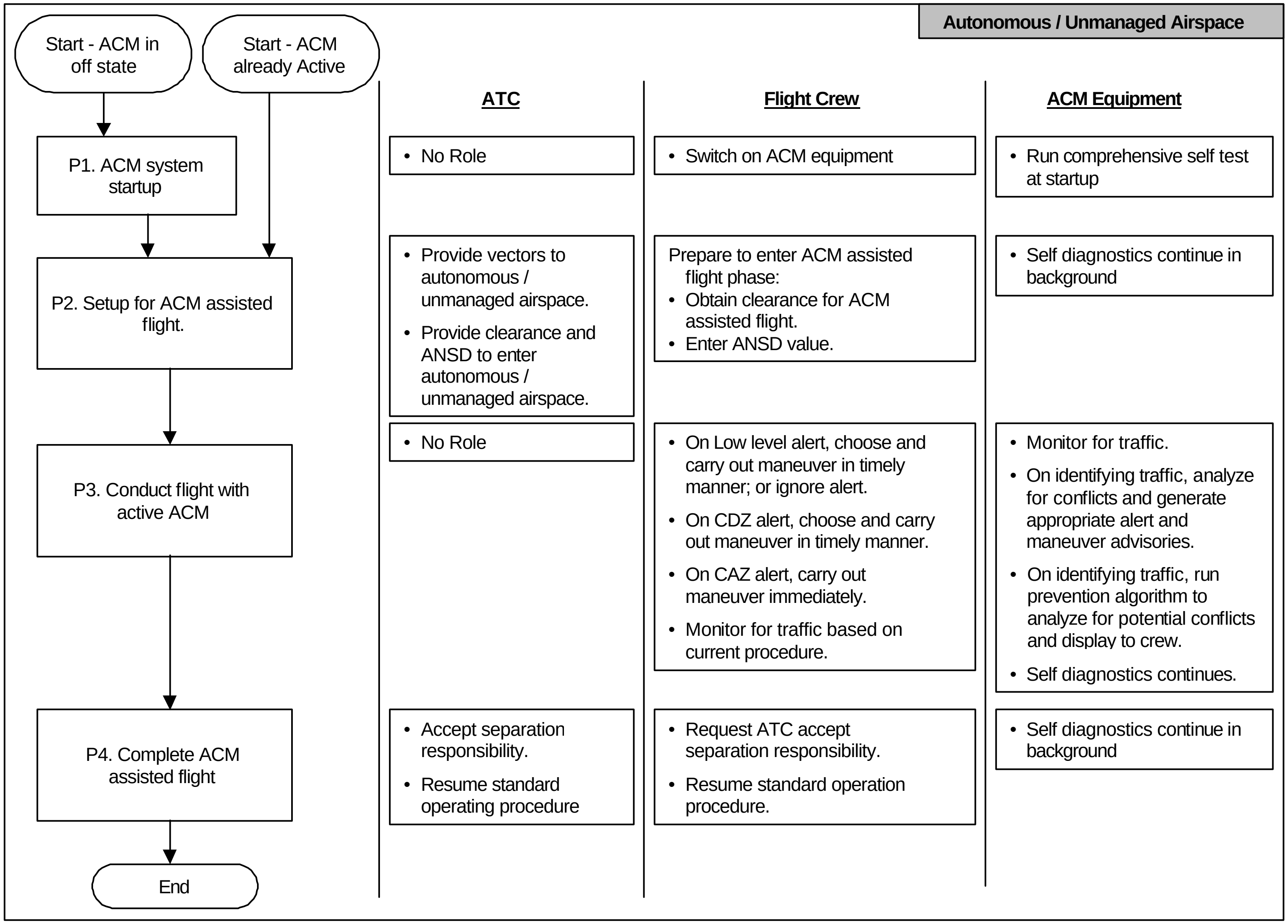
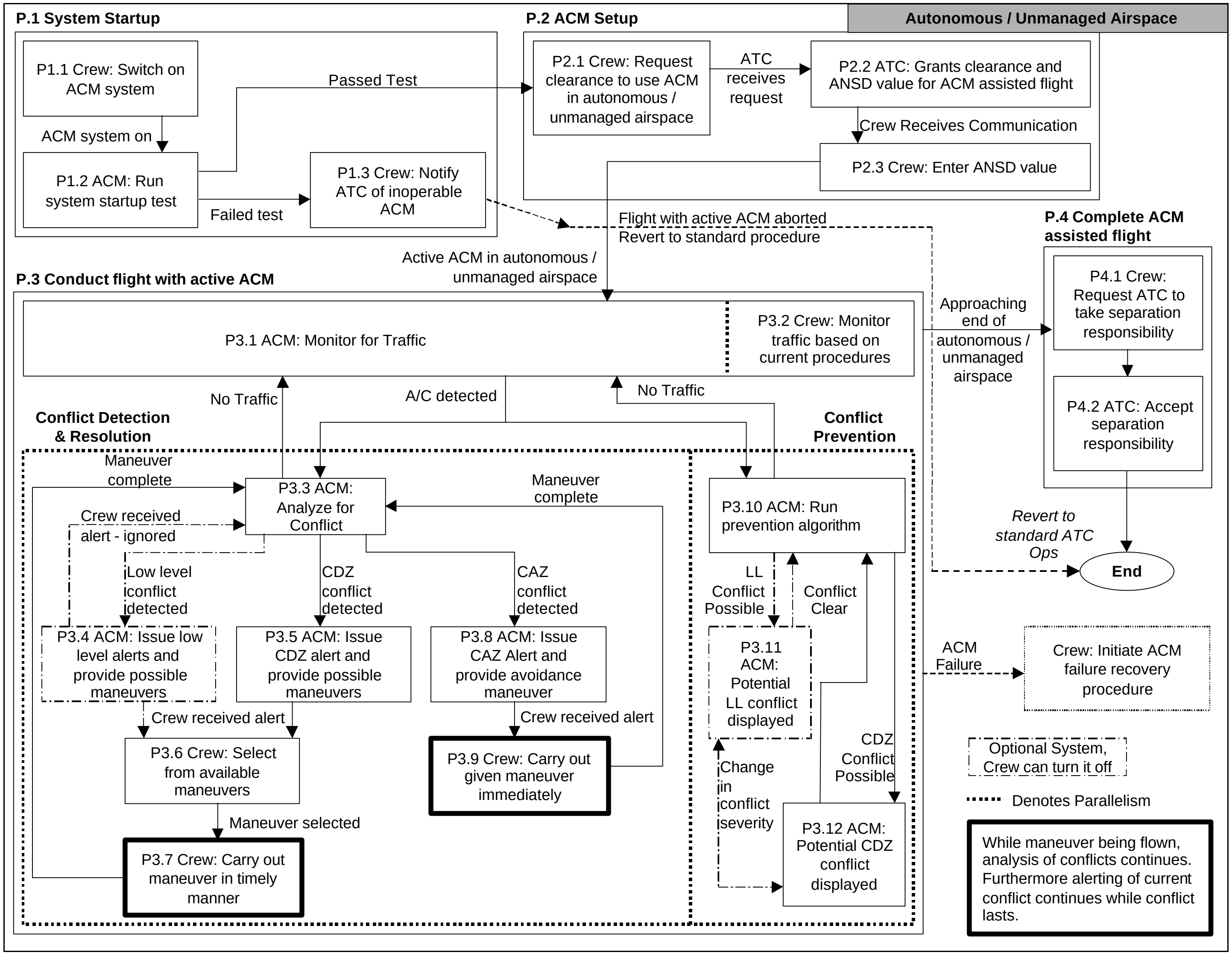


Figure 3: Phase Diagram – Autonomous/Unmanaged Airspace


P.1 System Startup
P.2 ACM Setup
Autonomous / Unmanaged Airspace
P1.1 Crew: Switch on ACM system
ACM system on
P1.2 ACM: Run system startup test
Passed Test
Failed test
P1.3 Crew: Notify ATC of inoperable ACM
P2.1 Crew: Request clearance to use ACM in autonomous / unmanaged airspace
ATC receives request
P2.2 ATC: Grants clearance and ANSD value for ACM assisted flight
Crew Receives Communication
P2.3 Crew: Enter ANSD value
Flight with active ACM aborted
Revert to standard procedure
Active ACM in autonomous / unmanaged airspace
P.3 Conduct flight with active ACM
P3.1 ACM: Monitor for Traffic
P3.2 Crew: Monitor traffic based on current procedures
No Traffic
A/C detected
No Traffic
Conflict Detection & Resolution
Conflict Prevention
Maneuver complete
P3.3 ACM: Analyze for Conflict
Maneuver complete
Crew received alert - ignored
Low level conflict detected
CDZ conflict detected
CAZ conflict detected
P3.4 ACM: Issue low level alerts and provide possible maneuvers
P3.5 ACM: Issue CDZ alert and provide possible maneuvers
P3.8 ACM: Issue CAZ Alert and provide avoidance maneuver
Crew received alert
Crew received alert
P3.6 Crew: Select from available maneuvers
P3.9 Crew: Carry out given maneuver immediately
Maneuver selected
P3.7 Crew: Carry out maneuver in timely manner
P3.10 ACM: Run prevention algorithm
LL Conflict Possible
Conflict Clear
P3.11 ACM: Potential LL conflict displayed
CDZ Conflict Possible
Change in conflict severity
P3.12 ACM: Potential CDZ conflict displayed
P.4 Complete ACM assisted flight
Approaching end of autonomous / unmanaged airspace
P4.1 Crew: Request ATC to take separation responsibility
P4.2 ATC: Accept separation responsibility
Revert to standard ATC Ops
End
ACM Failure
Crew: Initiate ACM failure recovery procedure
Optional System, Crew can turn it off
Denotes Parallelism
While maneuver being flown, analysis of conflicts continues. Furthermore alerting of current conflict continues while conflict lasts.

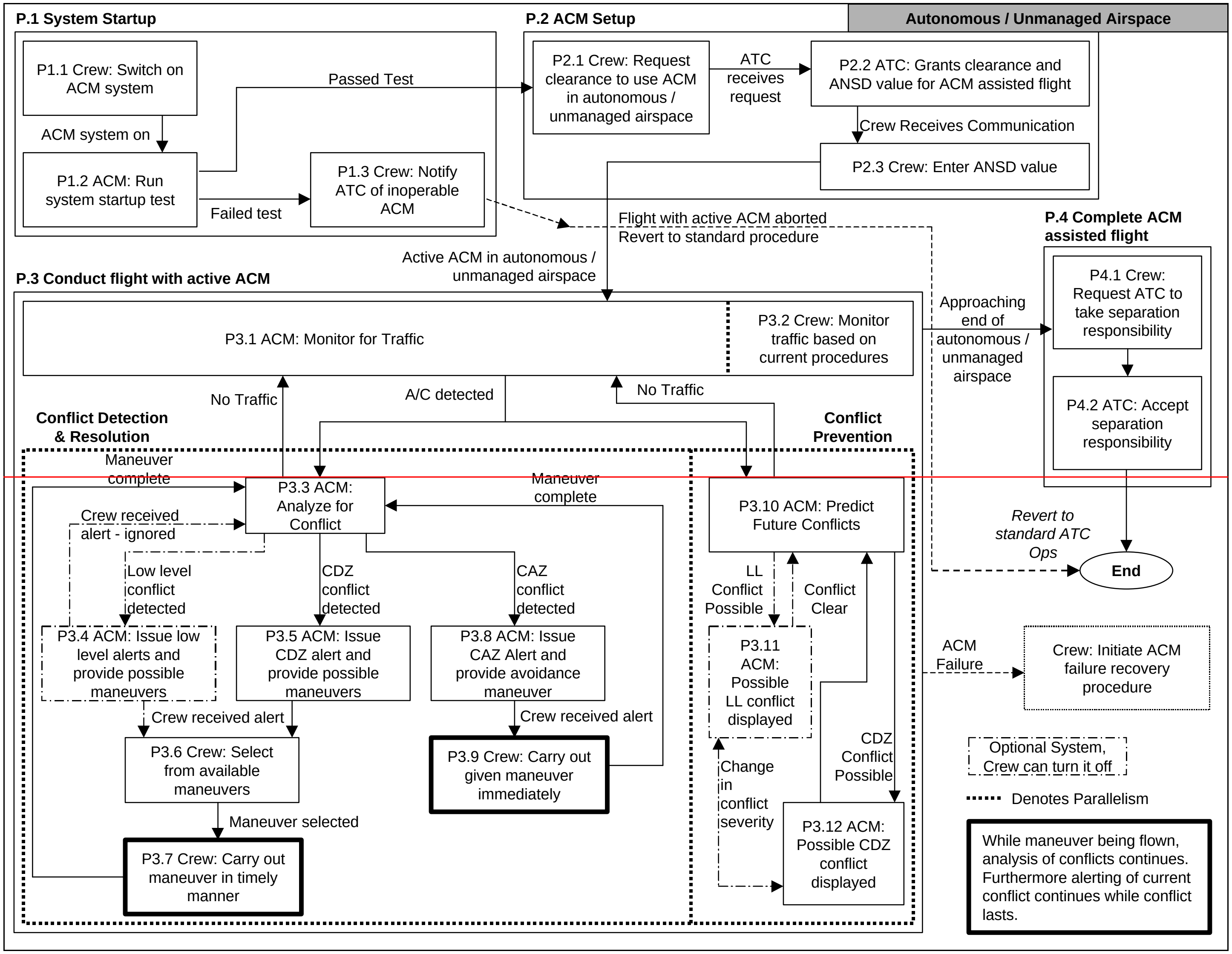
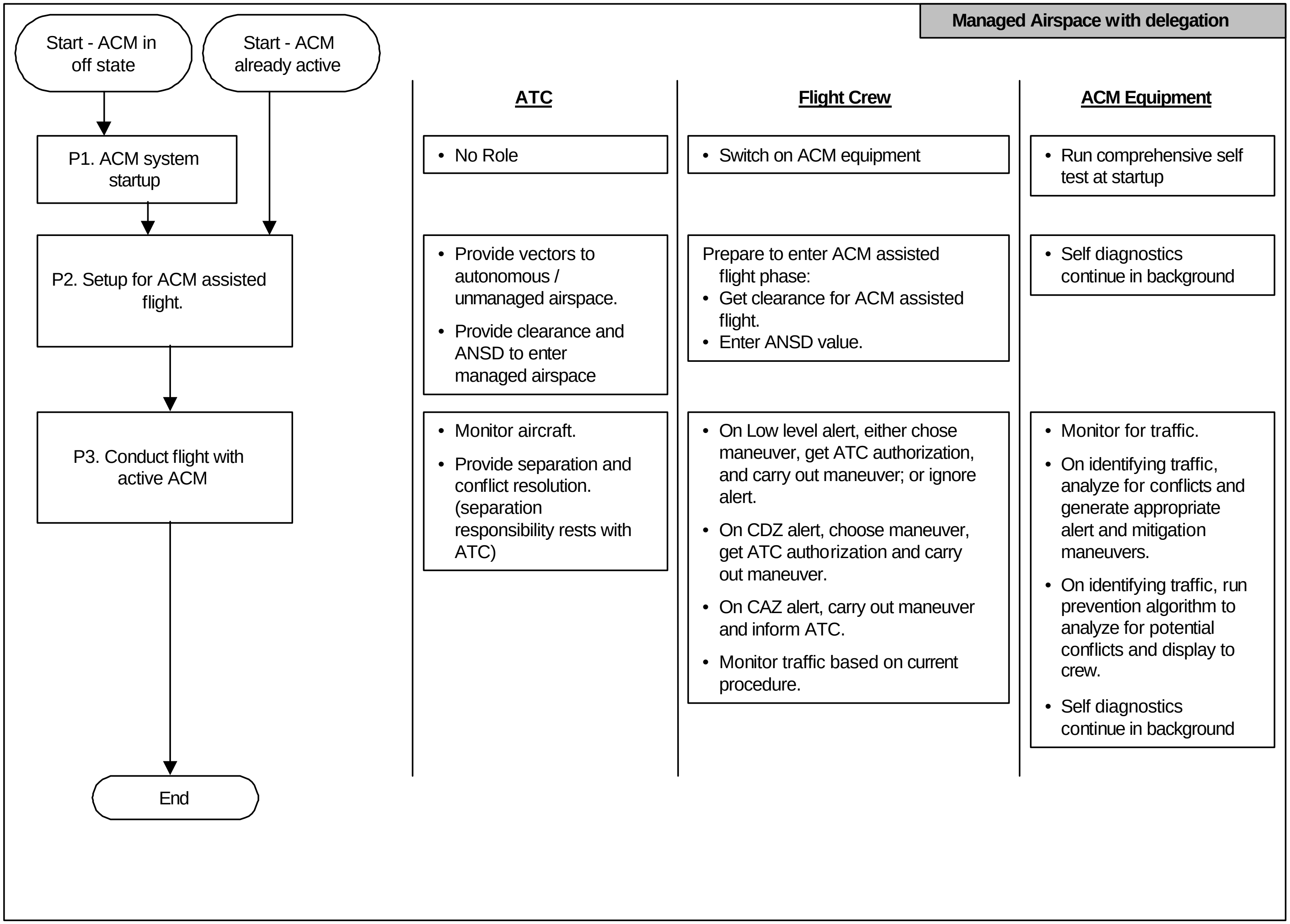


Figure 4: Process Diagram – Autonomous/Unmanaged Airspace


Managed Airspace with delegation
Start - ACM in off state
Start - ACM already active
P1. ACM system startup
P2. Setup for ACM assisted flight.
P3. Conduct flight with active ACM
End
ATC
Flight Crew
ACM Equipment
• No Role
• Switch on ACM equipment
• Run comprehensive self test at startup
• Provide vectors to autonomous / unmanaged airspace.
• Provide clearance and ANSD to enter managed airspace
Prepare to enter ACM assisted flight phase:
• Get clearance for ACM assisted flight.
• Enter ANSD value.
• Self diagnostics continue in background
• Monitor aircraft.
• Provide separation and conflict resolution. (separation responsibility rests with ATC)
• On Low level alert, either chose maneuver, get ATC authorization, and carry out maneuver; or ignore alert.
• On CDZ alert, choose maneuver, get ATC authorization and carry out maneuver.
• On CAZ alert, carry out maneuver and inform ATC.
• Monitor traffic based on current procedure.
• Monitor for traffic.
• On identifying traffic, analyze for conflicts and generate appropriate alert and mitigation maneuvers.
• On identifying traffic, run prevention algorithm to analyze for potential conflicts and display to crew.
• Self diagnostics continue in background

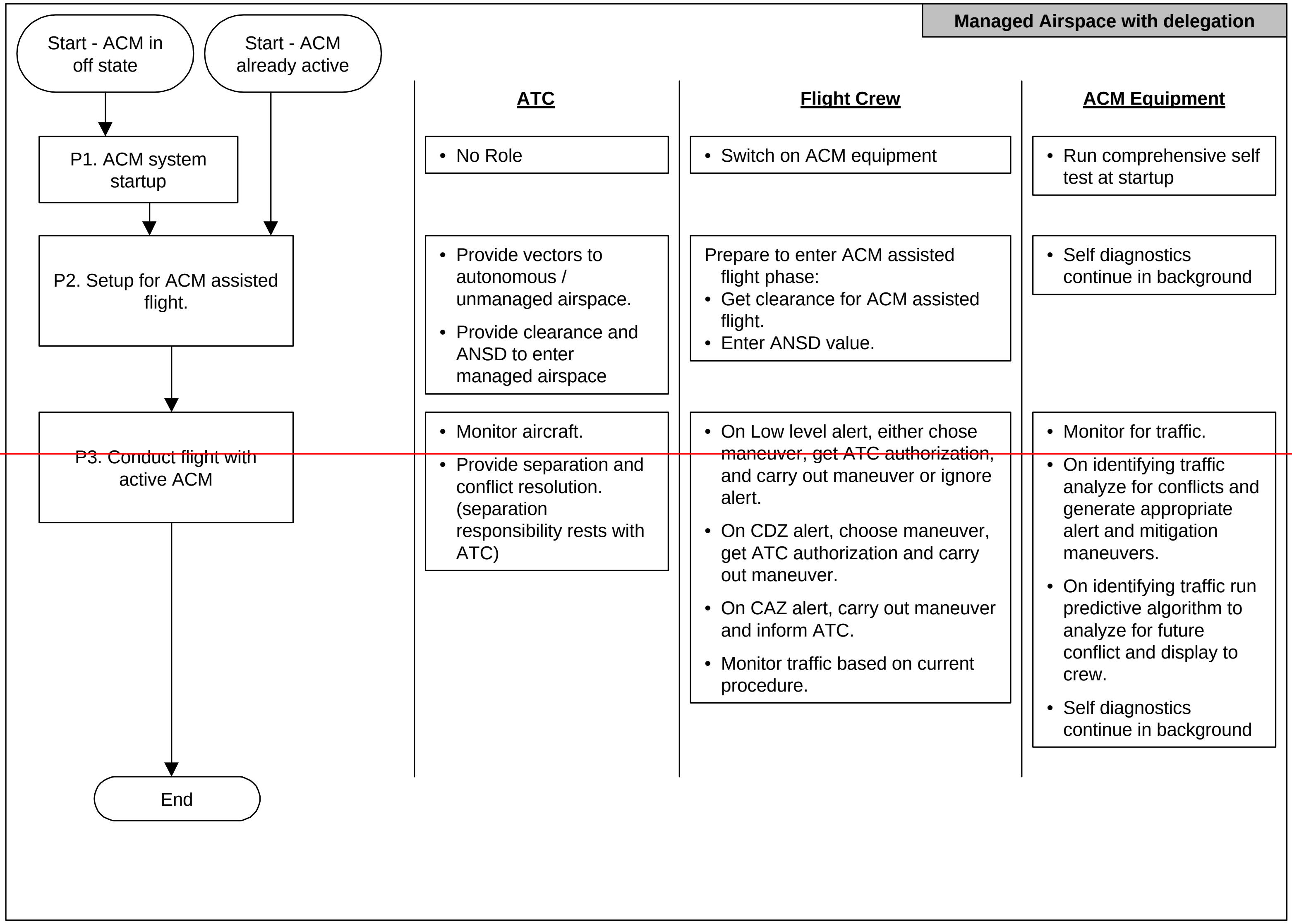
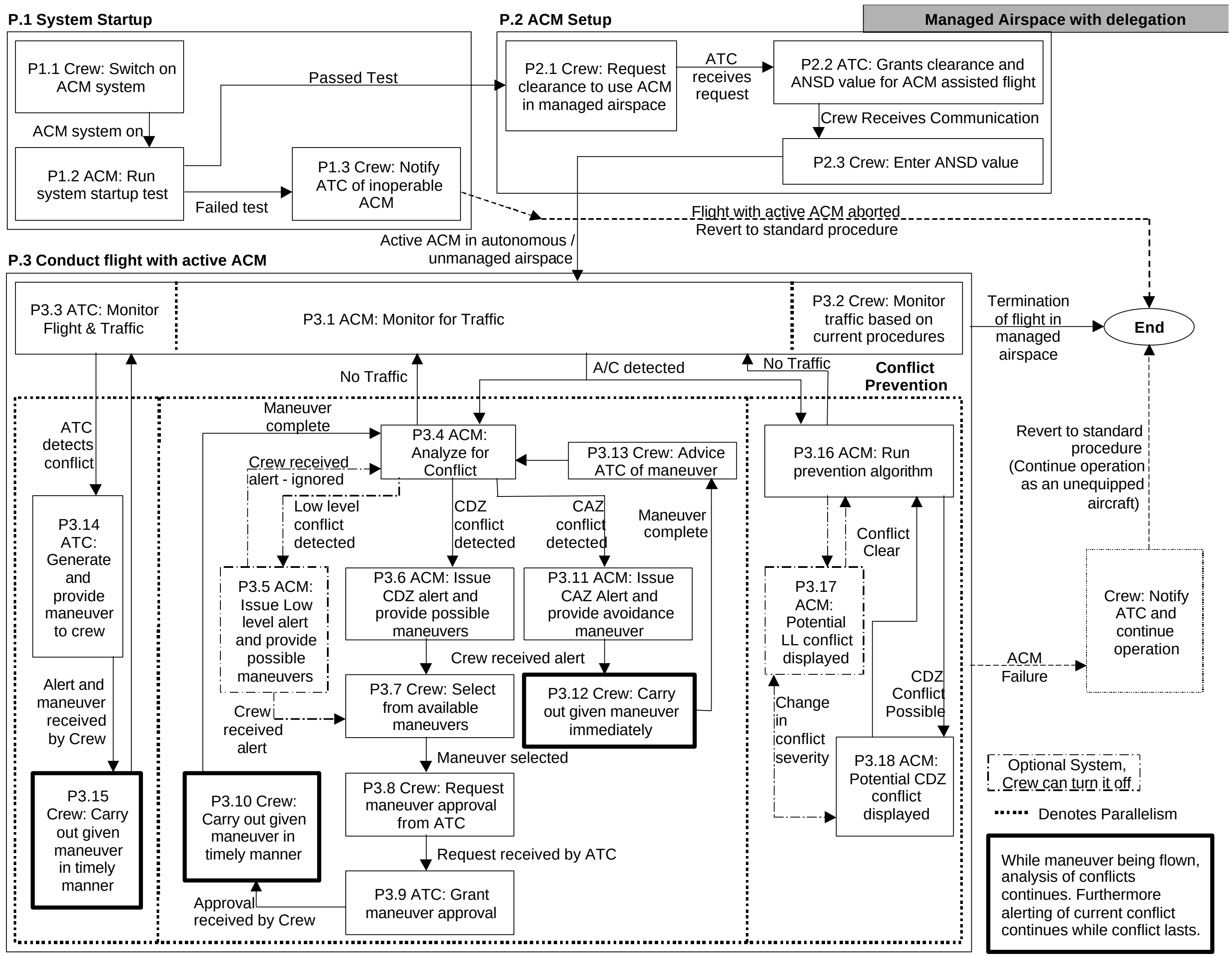


Figure 5: Phase Diagram – Managed Airspace


P.1 System Startup
P1.1 Crew: Switch on ACM system
ACM system on
P1.2 ACM: Run system startup test
Passed Test
Failed test
P1.3 Crew: Notify ATC of inoperable ACM
P.2 ACM Setup
Managed Airspace with delegation
P2.1 Crew: Request clearance to use ACM in managed airspace
ATC receives request
P2.2 ATC: Grants clearance and ANSD value for ACM assisted flight
Crew Receives Communication
P2.3 Crew: Enter ANSD value
Flight with active ACM aborted
Revert to standard procedure
Active ACM in autonomous / unmanaged airspace
P.3 Conduct flight with active ACM
P3.3 ATC: Monitor Flight & Traffic
P3.1 ACM: Monitor for Traffic
P3.2 Crew: Monitor traffic based on current procedures
Termination of flight in managed airspace
End
No Traffic
A/C detected
No Traffic
Conflict Prevention
ATC detects conflict
P3.14 ATC: Generate and provide maneuver to crew
Alert and maneuver received by Crew
P3.15 Crew: Carry out given maneuver in timely manner
Maneuver complete
P3.4 ACM: Analyze for Conflict
Crew received alert - ignored
P3.13 Crew: Advice ATC of maneuver
Low level conflict detected
CDZ conflict detected
CAZ conflict detected
Maneuver complete
P3.5 ACM: Issue Low level alert and provide possible maneuvers
P3.6 ACM: Issue CDZ alert and provide possible maneuvers
P3.11 ACM: Issue CAZ Alert and provide avoidance maneuver
Crew received alert
P3.7 Crew: Select from available maneuvers
P3.12 Crew: Carry out given maneuver immediately
Crew received alert
Maneuver selected
P3.10 Crew: Carry out given maneuver in timely manner
P3.8 Crew: Request maneuver approval from ATC
Request received by ATC
Approval received by Crew
P3.9 ATC: Grant maneuver approval
P3.16 ACM: Run prevention algorithm
Conflict Clear
P3.17 ACM: Potential LL conflict displayed
CDZ Conflict Possible
Change in conflict severity
P3.18 ACM: Potential CDZ conflict displayed
Revert to standard procedure (Continue operation as an unequipped aircraft)
Crew: Notify ATC and continue operation
ACM Failure
Optional System, Crew can turn it off
Denotes Parallelism
While maneuver being flown, analysis of conflicts continues. Furthermore alerting of current conflict continues while conflict lasts.

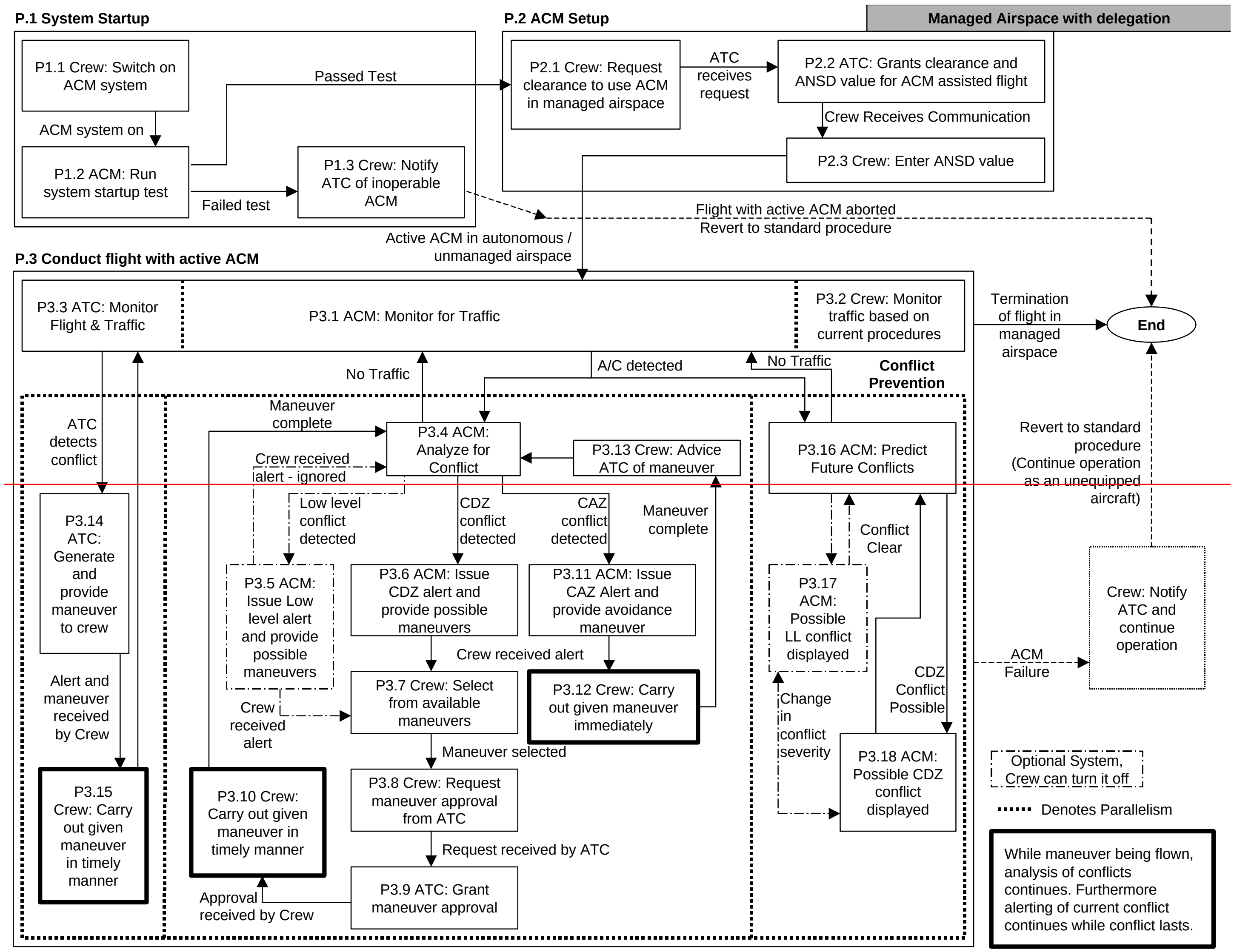


Figure 6: Process Diagram – Managed Airspace

2.3 Hazard and Safety Analysis

2.3.1 Operational Hazard Analysis

The hazard analysis for ACM is based on careful analysis of the phase and processes diagrams illustrated above in Figure 4 and Figure 6. Hazards are identified for each process by posing two hypotheses:

1. The process does not complete normally.
2. The process completes based on erroneous information or assumptions.

These two hypotheses form the basis of the hazard analysis presented in Table 3 and Table 4.

Table 3 provides a hazard analysis for flight in autonomous/unmanaged airspace, while Table 4 provides a hazard analysis for flight in managed airspace. Each hazard is identified with a unique phase and process number for future reference.

In both tables the first two columns list the phases and processes corresponding to the ones identified in Figure 4 and Figure 6. The third column lists the major hazards that can be faced for each process, followed by the possible consequences of these hazards in the next column. A consequence of the hazard is not necessarily immediate, and may occur due to a combination of events. Some of these are expanded on in the fault trees in 2.4.

The column labeled “causes” lists some possible causes of the hazard. The list is provided for illustrative purposes and is not exhaustive; again, the fault-tree analysis provided in 2.4 derives the potential causes of the relevant hazards in detail. The causes listed in Table 3 and Table 4 are useful to identify those hazards that require further analysis in terms of ACM and its supporting subsystems. For example, a hazard that is identified as being caused primarily by “human error,” or “communications system failure,” would not undergo additional fault tree analysis for the purposes of this study.

The column labeled “avoidances” lists some factors that can help to reduce the probability of the hazard from occurring. The last column labeled “mitigations” lists some factors that help to reduce the probability of the potential consequences once the hazard has occurred. Both these columns provide a summary and are not exhaustive.

2.3.2 Hazards analysis of ACM in Autonomous/Unmanaged Airspace

The following sections explain the rationale for entries in Table 3.

2.3.2.1 Hazards for Phase 1

The hazard of not switching on the ACM system is identified in H1.1.1. This is probably caused by human error and leads to ACM not being used in flight.

Hazard 1.2.1 identifies that the self test indicates a failure, which disables ACM. This would limit the crew to standard procedures, preventing it from entering autonomous airspace. A more dangerous hazard is 1.2.2 where the self test passes even when ACM is inoperative. In this case, it is conceivable that the flight crew flying solely on the basis of ACM could end up in a mid-air collision.

Process 1.3 describes communication failures between ATC and the flight crew. The two main hazards (which are identified here and used throughout this safety table) are that the communication is not received, or that the communication is received but misunderstood. In both cases current operational procedures would be used to attempt to establish contact. One possible consequence is that the planned procedure is aborted.

2.3.2.2 Hazards for Phase 2

Processes 2.1 and 2.2. indicate communication between the ATC and the crew for clearance to enter the autonomous airspace and receive the correct ANSD value. The hazards faced in these processes are similar as those in P1.3. The main difference is that in P2.2 the crew could misunderstand the ANSD value provided and use a wrong separation distance for autonomous flight.

The hazard related to entering the ANSD values are captured in H2.3.1 through~~and~~ H2.3.3~~2~~. H2.3.1 occurs when the crew does not enter any ANSD value. In this case the ACM system will use either a default value or a previously entered number. The second hazard is that the crew could enter an incorrect ANSD value. For these~~both~~ hazards the crew would end up flying with the perception of a different separation distance than what ACM will follow. ACM alerts could come after loss of separation has occurred (using too small an ANSD value), or when none are necessary (using too large an ANSD value).

2.3.2.3 Hazards for Phase 3

In P3.1.1 the main hazard is that ACM fails to detect traffic. This probably occurs due to navigation system failures. Such failures could lead to loss of separation and a mid-air collision due to missed alerts.

Hazard P3.1.2 is due to erroneous target detection. This could result in erroneous or missed alerts on actual conflicting aircraft, resulting in loss of separation and mid-air collision. It could also result in increased workload, as false alerts are issued based on this erroneous information.

Hazard 3.2.1 identifies the possibility that ACM may distract the crew from carrying out normal see-and-avoid procedures. This would have no consequence in autonomous airspace, as all airplanes will be equipped. However, it could lead to loss of separation or even a mid-air collision in unmanaged airspace as all aircraft are not equipped.

The main hazards while analyzing for conflicts (P3.3) include failing to identify a conflict (H3.3.1) or misidentifying the severity of the conflict (H3.3.2). In both cases the potential outcome could be a mid-air collision. There are various mitigation methods in place to avoid this, which are further explored in the fault tree analysis in 2.4.

Hazards 3.4.1, 3.4.2, 3.4.3, and 3.4.4 deal with the failure to alert on time or failure to provide the right maneuvers when a low level conflict is recognized. For a low level alert this has no major consequence as the distance (or time) to loss of separation is considerable and there are still CAZ and CDZ alerts to fall back on.

Hazards 3.5.1 through 3.5.4 are the same as 3.4.1 through 3.4.4. However, this time the failure is in the CDZ alerting and maneuver advisories. Hazard 3.5.3 is different because it is a false alert and would lead to increased workload. The other hazards could directly lead to a loss of separation as ANSD is violated.

Hazards 3.6.1 and 3.7.1 deal with the crew failing to comply with the maneuver advisory correctly or in a timely manner, which could lead to a loss of separation. This is caused mainly due to crew error and can be avoided by proper training.

Failure to issue a CAZ (P3.8) alert or to provide a correct maneuver directly leads to a potential mid-air collision. All alerting and maneuver advisory hazards for CAZ are the same as those for CDZ and low level alerts. However, due to the minimal spacing protected by the CAZ alert, a failure is likely catastrophic. A false alert as in H3.8.3 would lead to an increased workload for the pilot, although a CDZ or low level alert may exist. Hazard 3.9.1 leads to a mid-air collision as well, as the crew fails to follow a CAZ alert correctly or in a timely manner. This again can be avoided by proper training.

The next processes deal with the conflict prevention function of ACM. As this is essentially a situational awareness tool that helps reduce the probability of maneuvering to a conflicting path, there are no direct catastrophic consequences of failure of this system.

For processes 3.10, 3.11, and 3.12, there are two main hazards. One is failure to detect or display a potential~~ssible~~ future conflict, and the second is to provide or display a false prediction. In the first case, the result is a lack of situational awareness that may lead to a conflict. The alert time for such a conflict may be reduced~~, and the loss of the mitigation to failure of the CD&R function~~. In the second case, it could lead the crew to avoid a region that would not actually cause a conflict. Furthermore, a region shown as a potential~~ssible~~ conflict where no conflict would exist~~s~~ could erode confidence and lead to the crew spending more time considering ACM guidance before acting on that guidance. It could also cause increased workload due to unnecessary changes to planned courses.

2.3.2.4 Hazards for Phase 4

All hazards in this phase are communication hazards during the hand off of separation responsibility to ATC. These hazards all lead to increased workload as the crew has to repeat communication or follow another pre-defined procedure before entering the controlled airspace.

Phase	Processes	Hazard	Possible Consequences	Causes	Avoidances	Mitigations
P1Setup	P1.1 Crew: Switch on ACM system	H1.1.1 Does not switch on ACM system	No ACM functionality	Human error	Training, Clear mode annunciation	
	P1.2 ACM: Run system startup test.	H1.2.1 Test Fails	No ACM functionality	ACM equipment failure	System requirements	
		H1.2.2 Test passes even though ACM inoperative	Mid-air collision	ACM equipment failure	System requirements	Target ACM is operational, ATC monitoring, see and avoid
	P1.3 Crew: Notify ATC of inoperative ACM	H1.3.1 Notification not received	ATC unaware of inoperative ACM	Communication equipment failure	System requirements	Revert to standard procedure
		H1.3.2 Notification misunderstood	ATC unaware of inoperative ACM	Human error	Training	ATC monitoring, Revert to standard procedure
P2.Startup	P2.1 Crew: Request clearance to enter autonomous airspace airspace	H2.1.1 Request not received by ATC	Clearance not received	Communication equipment failure	System requirements	Revert to standard procedure
		H2.1.2 Request misunderstood by ATC	Clearance not received	Human error	Training	Revert to standard procedure
	P2.2 ATC: Give Clearance and ANSD for ACM Assisted flight	H2.2.1 Communication not received by Crew	Clearance not received	Comm. equipment failure	System requirements	Revert to standard procedure
		H2.2.2 Communication misunderstood by Crew	Clearance not received or misunderstood	Human error	Training	ATC monitoring
	P2.3 Crew: Enter ANSD value	H2.3.1 No distance entered	Loss of separation (uses previous value)	Human error	Training	
		H2.3.2 ANSD entry too small~~Incorrect distance entered~~	Loss of separation	Human error	Multiple confirmation, reasonableness checks	Target ACM is operational
		H2.3.3 ANSD entry too large	Increased workload	Human error	Training	

Phase	Processes	Hazard	Possible Consequences	Causes	Avoidances	Mitigations
P3. ACM Autonomous Flight	P3.1 ACM: Monitor for Traffic	H3.1.1 Traffic not detected	Mid-air collision.	equipment failure, unequipped aircraft	Integrity and continuity requirements	Target detects ownship, see and avoid
		H3.1.2 Traffic mis-detected	Mid-air collision / Increased workload	Equipment failure, Unequipped aircraft	Integrity and continuity requirements	see and avoid
	P3.2 Crew: Monitor traffic based on current procedures	H3.2.1 ACM distracts crew from normal monitoring	Loss of separation	Human error	Training	Target detects ownship
	P3.3 ACM: Analyze for Conflict	H3.3.1 Fails to identify correct conflict	Mid-air collision	Equipment failure	Integrity and continuity requirements	Target ACM is operational, see and avoid~~, Conflict Prevention Operational~~
		H3.3.2 Non-conflict shown as conflict	Increased workload	Equipment failure	Integrity and continuity requirements	
		H3.3.3 Severity of conflict misidentified	Mid-air collision	Equipment failure	Integrity and continuity requirements, Crew training	Target ACM is operational, see and avoid~~, Conflict Prevention Operational~~
	P3.4 ACM: Issue low level alert and provide possible maneuvers	H3.4.1 Missed alert	Lack of long term awareness	Equipment failure	System requirements	~~Conflict Prevention Operational,~~ CDTI operational
		H3.4.2 Fails to provide maneuvers	Increased workload	Equipment failure	System requirements, Crew training	Revert to standard procedure
		H3.4.3 Issues false alert	Increased workload	Equipment failure	Integrity and continuity requirements	

Phase	Processes	Hazard	Possible Consequences	Causes	Avoidances	Mitigations
		H3.4.4 Provides maneuver that doesn't solve conflict	Increased workload	Equipment failure	Integrity and continuity requirements, Crew training	CDTI operational
	P3.5 ACM: Issue CDZ alert and provide possible maneuvers	H3.5.1 Missed alert	Loss of separation	Equipment failure	System requirements	Target ACM is operational~~, Conflict Prevention Operational~~
		H3.5.2 Fails to provide maneuvers	Loss of separation	Equipment failure	Crew Training, System Requirements	Revert to standard procedure
		H3.5.3 Issues false alert	Increased workload	Equipment failure	Integrity and continuity requirements	
		H3.5.4 Provides maneuver that doesn't solve conflict	Loss of separation	Equipment failure	Integrity and continuity requirements, Crew training	Target ACM is operational, CDTI operational
	P3.6 Crew: Select from available maneuvers	H3.6.1 Crew does not comply with ACM guidance	Loss of separation	Human error	Training, Proper system and display design	Target ACM is operational~~, Conflict Prevention Operational~~
	P3.7 Crew: Carry out given maneuver in timely manner	H3.7.1 Fail to follow maneuver correctly (time & action)	Loss of separation	Human error	Training, Proper system and display design	Target ACM is operational
	P3.8 ACM: Issue CAZ alert and provide ~~mitigation~~ maneuver	H3.8.1 Missed alert	Mid-air collision	Equipment failure	Integrity and continuity requirements	Target ACM is operational, CDTI operational. See and avoid
		H3.8.2 Fails to provide maneuver	Mid-air collision	Equipment failure	Integrity and continuity requirements	~~Revert to standard procedure~~See and avoid

Phase	Processes	Hazard	Possible Consequences	Causes	Avoidances	Mitigations
		H3.8.3 Issues false alert	Increased Workload	Equipment failure	System requirements	
		H3.8.4 Provides maneuver that doesn't solve conflict	Mid-air collision	Equipment failure	Integrity and continuity requirements	Target ACM is operational~~,~~ see and avoid ~~CP Operational~~
	P3.9 Crew: Carry out given maneuver immediately	H3.9.1 Failure to carry out maneuver (time & action)	Mid-air collision	Human error	Training	Target carries out necessary maneuver, see and avoid
	P3.10 ACM: Run prevention algorithm~~Predict Future Conflict~~	H3.10.1 Missed prediction	Conflict occurs; reduced conflict alert time ~~Lack of situational awareness~~	Equipment failure	System requirements	CDTI operational, visual
		H3.10.2~~1~~ False prediction	Increased workload~~Lead to conflict, reduced alert time~~	Equipment failure	Integrity and continuity requirements	CDTI operational, visual
	P3.11 ACM: Potential~~ssible~~ LL conflict displayed	H3.11.1 Fails to display	Conflict occurs; reduced conflict alert time ~~Lack of situational awareness~~	Equipment failure	System requirements	CDTI operational, visual
		H3.11.2~~1~~ False display	Increased workload~~Lead to conflict, reduced alert time~~	Equipment failure	Integrity and continuity requirements	CDTI operational, visual
	P3.12 ACM: Potential~~ssible~~ CDZ conflict displayed	H3.12.1 Fails to display	Conflict occurs; reduced conflict alert time ~~Lack of situational awareness~~	Equipment failure	System requirements	CDTI operational, visual
		H3.12.2~~1~~ False display	Increased workload~~Lead to conflict, reduced alert time~~	Equipment failure	Integrity and continuity requirements	CDTI operational, visual

Phase	Processes	Hazard	Possible Consequences	Causes	Avoidances	Mitigations
P4.Post ACM Assisted Flight	P4.1 Crew: Request ATC to take separation responsibility	H4.1.1 Communication not received by ATC	Increased workload	Equipment failure	System requirements	
		H4.1.2 Communication Misunderstood	Increased workload	Human error	Training	
	P4.2 ATC: Accept separation responsibility	H4.2.1 Communication not received	Increased workload	Equipment failure	System requirements	
		H4.2.2 Communication Misunderstood	Increased workload	Human error	Training	

Table 3: Operational Hazard Analysis of ACM in Autonomous/Unmanaged Airspace

2.3.3 Hazards for ACM in Managed Airspace

The following sections describe the hazards in each phase of flight in managed airspace with ACM based on the hazards described in Table 4.

2.3.3.1 Hazards for Phase 1

The processes are identical to the ones for autonomous/unmanaged airspace. Refer to section 2.3.2.1 for details.

2.3.3.2 Hazards for Phase 2

The processes are identical to the ones for autonomous/unmanaged airspace. Refer to section 2.3.2.2 for details.

2.3.3.3 Hazards for Phase 3

The processes and related hazards in phase 3 that are identical to the ones for autonomous/unmanaged airspace are not discussed here. Refer to 2.3.2.3 for details. Note that one key difference for managed airspace is that ATC monitoring acts as mitigation for most hazards.

P3.3 refers to ATC monitoring, which has hazards and consequences identical to present day monitoring.

Process 3.4 through 3.7 correspond to processes 3.3 through 3.6 for the autonomous/unmanaged airspace description in section 2.3.2.3.

Processes 3.8 and 3.9 are unique to managed airspace, as ATC approval is required ~~needs to provide approval~~ for the crew to fly a particular maneuver based on a CDZ or low level alert. Here the hazards are communication hazards, which could lead to loss of separation, as the crew would be unable to carry out the required maneuver in a timely manner.

H3.10.1 identifies the hazard of the crew not following the ACM advisories after receiving an approval from ATC. This could lead to loss of separation and can be avoided by proper training.

P3.11 and P3.12 correspond to P3.8 and P3.9 of the autonomous/unmanaged airspace and are discussed in section 2.3.2.3.

Once the CAZ maneuver is completed, the crew needs to inform ATC of the maneuver they have undertaken. Again, the hazards here are related to communication. Failure to provide this information to ATC could lead to loss of separation, as there could be other unequipped airplanes in the area.

Along with ACM, ATC is always monitoring the aircraft and providing conflict management in managed airspace (P3.14). This process of providing separation assurance is considered to be identical to current procedures and there is no role of ACM. However, it is possible that ATC might detect a conflict and provide a maneuver request at the same time as ACM does. In such a case, especially if it is a CAZ conflict, there is a possibility of pilot confusion if the provided maneuvers are different.

Process 3.15 is the same as 3.10 and faces the same hazards.

P3.16 through and P3.18 correspond to P3.10 through P3.12 of the autonomous/unmanaged airspace and are discussed in section 2.3.2.3.

Phase	Processes	Hazard	Possible Consequences	Causes	Avoidances	Mitigations
P1Setup	P1.1 Crew: Switch on ACM system	H1.1.1 Does not switch on ACM system	No ACM functionality	Human error	Training, Clear mode annunciation	
	P1.2 ACM: Run system startup test.	H1.2.1 Test Fails	No ACM functionality	ACM equipment failure	System requirements	Remain in managed airspace
		H1.2.2 Test passes even though ACM inoperative	Mid-air collision	ACM equipment failure	System requirements	Target ACM is operational, ATC monitoring, see and avoid
	P1.3 Crew: Notify ATC of inoperative ACM	H1.3.1 Notification not received	No ACM functionality	Communication equipment failure	System requirements	Revert to standard procedure
		H1.3.2 Notification misunderstood	No ACM functionality	Human error	Training	ATC monitoring, Revert to standard procedure
P2.Startup	P2.1 Crew: Request clearance to use ACM in managed airspace~~autonomous Airspace~~	H2.1.1 Request not received by ATC	Clearance not received	Communication equipment failure	System requirements	Revert to standard procedure
		H2.1.2 Request misunderstood by ATC	Clearance not received	Human error	Training	Revert to standard procedure
	P2.2 ATC: Give Clearance and ANSD for ACM Assisted flight	H2.2.1 Communication not received by Crew	Clearance not received	Comm. equipment failure	System requirements	Revert to standard procedure
		H2.2.2 Communication misunderstood by Crew	Clearance not received or misunderstood	Human error	Training	ATC monitoring
	P2.3 Crew: Enter ANSD value	H2.3.1 No distance entered	Loss of separation ~~(uses previous value)~~	Human error	Training	ATC monitoring
		H2.3.2 ANSD entry too small~~Incorrect distance entered~~	Loss of separation	Human error	Multiple confirmation, reasonableness checks	Target ACM is operational, ATC monitoring
		H2.3.3 ANSD entry too large	Increased workload	Human error	Training	ATC monitoring

Phase	Processes	Hazard	Possible Consequences	Causes	Avoidances	Mitigations
P3.ACM Assisted Flight Phase	P3.1 ACM: Monitor for Traffic	H3.1.1 Traffic not detected	Mid-air collision.	ACM equipment failure, CNS equipment failure	System Requirements	ATC monitoring, Target detects ownship, see and avoid
		H4.1.2 Traffic mis-detected	Mid-air collision / Increased workload	Equipment failure, Unequipped aircraft	Integrity and continuity requirements	ATC monitoring, see and avoid
	P3.2 Crew: Monitor traffic based on current procedures	H3.2.1 ACM distracts crew from normal monitoring	None	Human error	Training	ATC monitoring
	P3.3 ATC: Monitor Flight & Traffic	Identical to current operational procedures				
	P3.4 ACM: Analyze for Conflict	H3.4.1 Fails to identify correct conflict	Mid-air collision	ACM equipment failure	Integrity and continuity requirements	ATC monitoring, Target ACM is operational, see and avoid
		H3.4.2 Non-conflict shown as conflict	Increased workload	ACM equipment failure	Integrity and continuity requirements	ATC monitoring
		H3.4.3 Severity of conflict misidentified	Mid-air collision	ACM equipment failure	Integrity and continuity requirements, Crew training	ATC monitoring, Target ACM is operational
	P3.5 ACM: Issue low level alert and provide possible maneuvers	H3.5.1 Missed alert	Lack of long term awareness	ACM equipment failure	System requirements	ATC monitoring, see and avoid~~,~~ ~~Conflict Prevention operational~~
		H3.5.2 Fails to provide maneuvers	Increased workload	ACM equipment failure	System requirements, Crew training	Revert to standard procedure
		H3.5.3 Issues false alert	Increased workload	ACM equipment failure	Integrity and continuity requirements	ATC monitoring
		H3.5.4 Provides maneuver that doesn't solve conflict	Loss of separation, Increased workload	ACM equipment failure	Integrity and continuity requirements, Crew training	ATC monitoring, CDTI operational

Table 4: Operational Hazard Analysis of ACM in Managed Airspace: Operational Hazard Analysis of ACM in Managed Airspace

Phase	Processes	Hazard	Possible Consequences	Causes	Avoidances	Mitigations
	P3.6 ACM: Issue CDZ alert and provide possible maneuvers	H3.6.1 Missed alert	Loss of separation	ACM equipment failure	System requirements	ATC monitoring, Target ACM is operational
		H3.6.2 Fails to provide maneuvers	Loss of separation	ACM equipment failure	Crew Training, System Requirements	ATC monitoring, Revert to standard procedure
		H3.6.3 Issues false alert	Increased workload	ACM equipment failure	Integrity and continuity requirements	ATC monitoring
		H3.6.4 Provides maneuver that doesn't solve conflict	Loss of separation	ACM equipment failure	Integrity and continuity requirements, Crew training	ATC monitoring, Target ACM is operational
	P3.7 Crew: Select from available maneuvers	H3.7.1 Crew does not comply with ACM guidance	Loss of separation	Human error	Training, Proper system and display design	ATC monitoring, Target ACM is operational
	P3.8 Crew: Request maneuver approval from ATC	H3.8.1 Crew Request not received by ATC	Increased workload	Communication equipment failure	System requirements	ATC monitoring, Revert to standard procedure
		H3.8.2~~1~~ Crew Request misunderstood by ATC	Increased workload, loss of separation	Human error	Training	Revert to standard procedure
	P3.9 ATC: Grant maneuver approval	H3.9.1 ATC Approval not received by crew	Loss of separation	Communication equipment failure	System requirements	ATC monitoring, Revert to standard procedure
		H3.9.2~~1~~ ATC Approval misunderstood by crew	Increased workload, loss of separation	Human error	Training	Revert to standard procedure
	P3.10 Crew: Carry out given maneuver in timely manner	H3.10.1 Fail to follow maneuver correctly (time & action)	Loss of separation	Human error	Training, Proper system and display design	ATC monitoring, Target ACM is operational
	P3.11 ACM: Issue CAZ alert and provide ~~mitigation~~ maneuver	H3.11.1 Missed alert	Mid-air collision	ACM equipment failure	Integrity and continuity requirements	ATC monitoring, Target ACM is operational, see and avoid

Phase	Processes	Hazard	Possible Consequences	Causes	Avoidances	Mitigations
		H3.11.2 Fails to provide maneuver	Mid-air collision	ACM equipment failure	Integrity and continuity requirements	ATC monitoring, see and avoid~~,~~ ~~Revert to standard procedure~~
		H3.11.3 Issues false alert	Increased Workload	ACM equipment failure	System requirements	
		H3.11.4 Provides maneuver that doesn't solve conflict	Mid-air collision	ACM equipment failure	Integrity and continuity requirements	ATC monitoring, Target ACM is operational, see and avoid
	P3.12 Crew: Carry out given maneuver immediately	H3.12.1 Failure to carry out maneuver immediately or correctly	Mid-air collision	Human error	Training	ATC monitoring,. Target carries out necessary maneuver, see and avoid
	P3.13 Crew: Advise ATC of maneuver	H3.13.1 Crew update not received by ATC	Loss of separation	Communication equipment failure	System requirements	ATC monitoring
		H3.13.2 Crew update misunderstood by ATC	Loss of separation	Human error	Training	ATC monitoring
	P3.14 ATC: Generate and provide maneuver to crew	H3.14.1 ATC provides conflicting maneuver to that provided by ACM (occurs at same time)	Pilot confusion, mid-air collision	Human error	Training	See and avoid
	P3.15 Crew: Carry out given maneuver in timely manner	H3.15.1 Failure to carry out maneuver immediately or correctly	Mid-air collision	Human error	Training	ATC monitoring,. Target carries out necessary maneuver, see and avoid
	P3.16 ACM: Run prevention algorithm~~Predict Future Conflict~~	H3.16.1 Missed prediction	Conflict occurs; reduced conflict alert time~~Lack of situational awareness~~	Equipment failure	System requirements	CDTI operational, visual

Phase	Processes	Hazard	Possible Consequences	Causes	Avoidances	Mitigations
		H3.16.2~~1~~ False prediction	Increased workload~~Lead to conflict, reduced alert time~~	Equipment failure	Integrity and continuity requirements	CDTI operational, visual
	P3.17 ACM: Potential~~ssible~~ LL conflict displayed	H3.17.1 Fails to display	Conflict occurs; reduced conflict alert time~~Lack of situational awareness~~	Equipment failure	System requirements	CDTI operational, visual
		H3.17.2~~1~~ False display	Increased workload~~Lead to conflict, reduced alert time~~	Equipment failure	Integrity and continuity requirements	CDTI operational, visual
	P3.18 ACM: Potential~~ssible~~ CDZ conflict displayed	H3.18.1 Fails to display	Conflict occurs; reduced conflict alert time~~Lack of situational awareness~~	Equipment failure	System requirements	CDTI operational, visual
		H3.18.2~~1~~ False display	Increased workload~~Lead to conflict, reduced reaction time~~	Equipment failure	Integrity and continuity requirements	CDTI operational, visual

Table 4: Operational Hazard Analysis of ACM in Managed Airspace

2.4 Fault Tree Analysis

The main consequence of significant criticality as identified in the safety tables above is a mid-air collision.

Another important consequence is loss of separation. However, as loss of separation is a necessary condition for a mid-air collision, loss of separation is analyzed as part of the analysis of mid-air collision.

Of the two main operating environments, providing assured separation in autonomous airspace is the more challenging environment for ACM. For managed airspace, the fault tree analyzing mid-air collision would be almost the same except for an added layer of security due to the availability of ATC monitoring as a mitigating factor.

Due to the above reasons, a fault tree analysis of mid-air collision for ACM in an autonomous environment is provided here. (Unmanaged airspace is not elaborated on here, but ACM would be effective in unmanaged airspace for aircraft equipped with ADS-B. ACM is ineffective against non-ADS-B-equipped aircraft in unmanaged airspace.)

Other consequences of ACM are not explored in detail here, as they are not deemed critical to the safety of the application.

Note that all failure rates used in the analysis are per flight hour.

The analysis begins by considering the top-level failures shown in Figure 7 which are required to cause a mid-air collision.

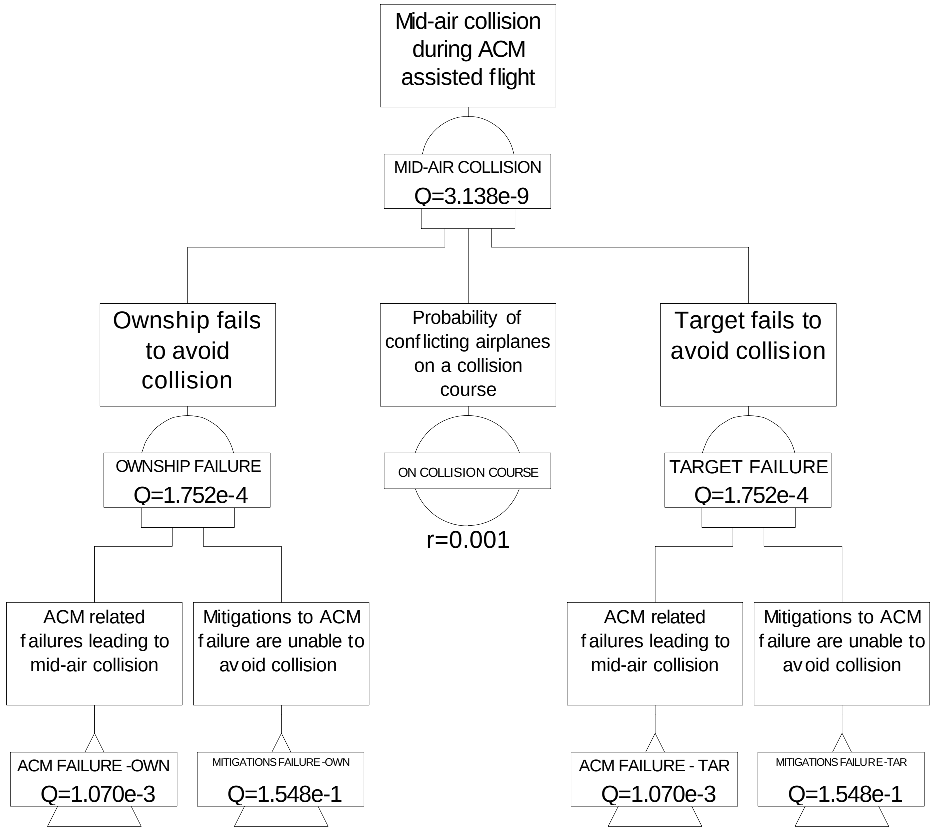


Figure 7: High Level Fault Tree for Mid-Air Collision Analysis

As can be seen in Figure 7 a 3×10^{-9} failure rate is achievable while using the ACM application as a primary means of separation assurance.

A mid-air collision can only occur when two airplanes are on a collision course and both the airplanes fail to avoid the collision.

An important assumption is the probability that the airplanes are on a collision course. The conservative value of 10^{-3} per flight hour has been chosen.

The fault trees for ownship and target failure, while largely independent, are essentially the same in content. So the description of the Ownship Failure provided here applies to Target Failure as well. The few common mode failures between them are described separately.

2.4.1 Fault Tree Analysis of Ownship Related Failures

For an airplane to fail to avoid a collision in autonomous airspace, a number of ACM-related failures need to occur along with the failure of all available mitigation methods as shown in Figure 7.

2.4.1.1 Fault tree analysis of ACM Failure on Ownship

Figure 8 presents the fault tree for ACM related failures on the ownship.

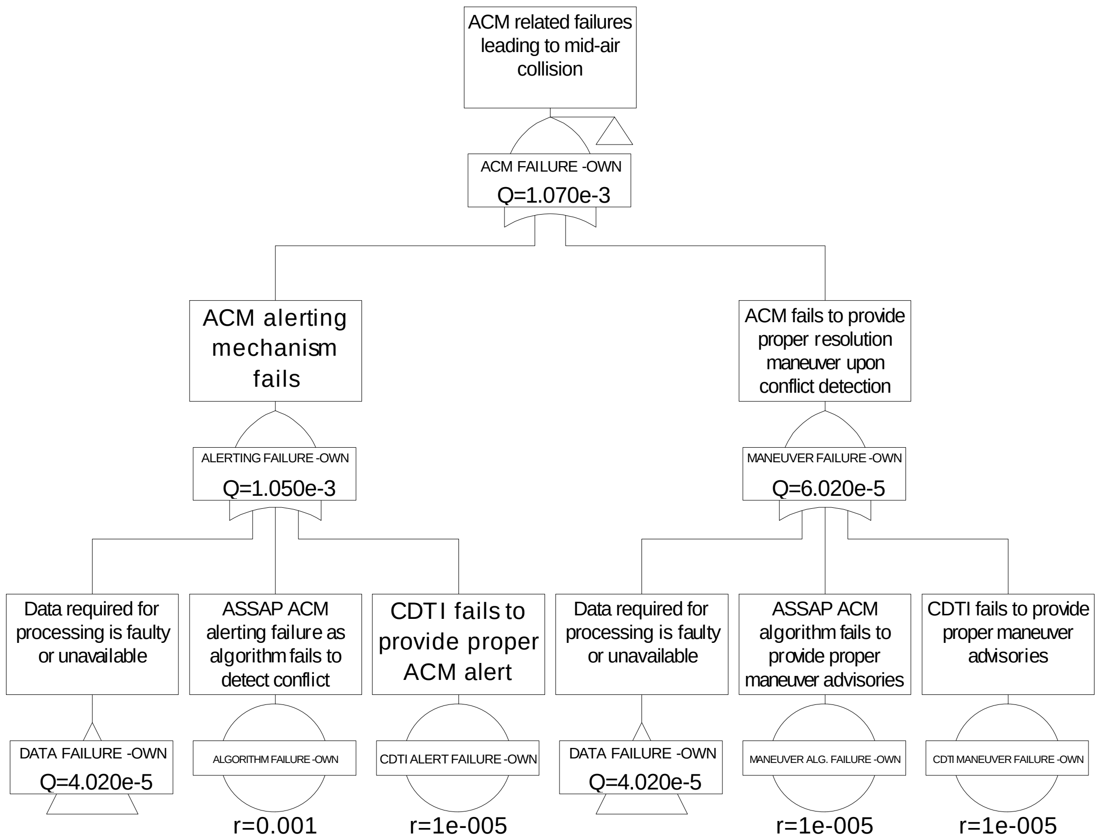


Figure 8: Fault tree of ACM failure on Ownship

Here the failures that can lead to a mid-air collision include the failure of the ACM alerting function or of the maneuver providing function.

The ACM alerting mechanism can fail due to various reasons. Bad input data to the processing function could cause the alerting mechanism fail. There are various sources of bad input data that are expanded upon in Figure 9. The alerting mechanism could also fail to alert due to failure of the algorithm itself or of the CDTI in conveying the alert to the crew.

The mechanism that provides the maneuvers could fail in ways similar to those of the alerting mechanism failure. It is affected by the inputs, the algorithm, and the ability of the CDTI to communicate the maneuvers to the crew. Any of these causes will lead to failure of the maneuver advisory system.

2.4.1.1.1 Fault tree analysis of Data Input Errors

Figure 11 presents the fault tree for data input errors.

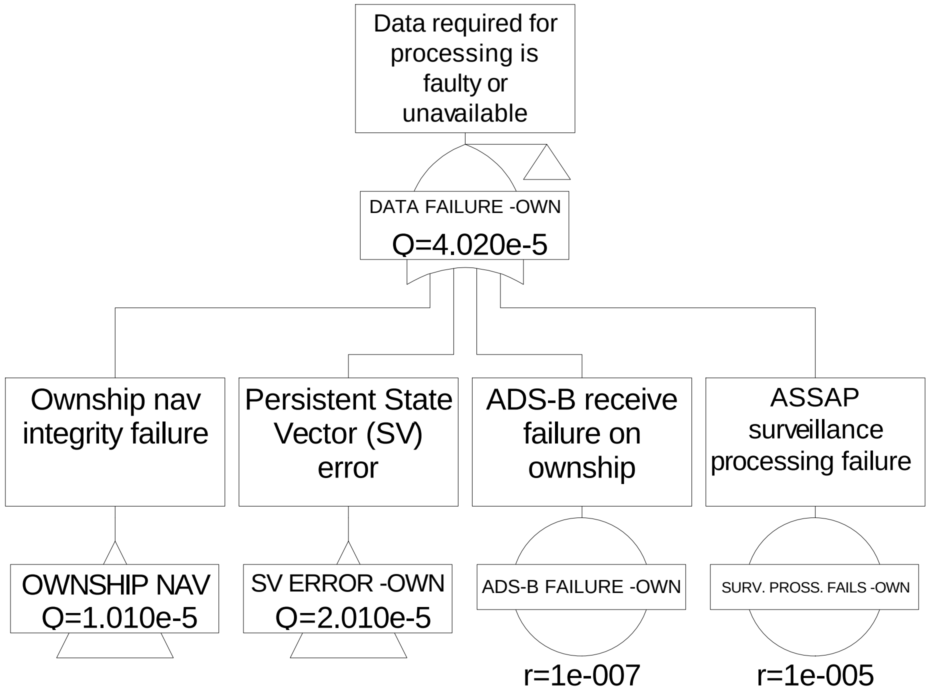


Figure 9: Fault tree of Data Input Failures

As shown in Figure 9, there are four sources of possible errors in the data input. The first is a navigation failure on ownship. This is further expanded in section 2.4.1.1.2. The second is a persistent state vector error in the data being received from the target, which occurs due to various reasons as described in section 2.4.1.1.3. Another reason for not having the correct data is the failure of the ADS-B receiver on ownship. Finally, the failure of the ASSAP surveillance processing module could cause the data being received by the ASSAP application to have errors.

2.4.1.1.2 Fault tree analysis of Ownship Navigation Integrity Failure

Figure 10 presents the fault tree for a persistent state vector (SV) error on ownship.

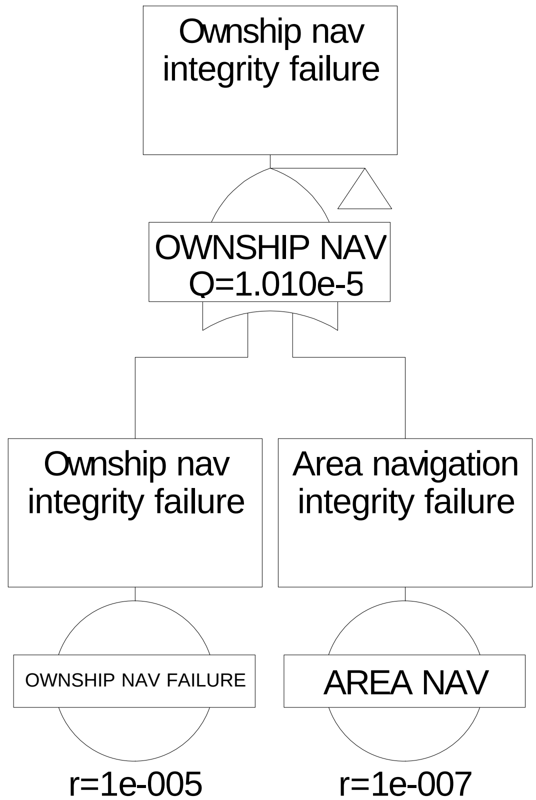


Figure 10: Fault Tree of Ownship Navigation Integrity Failure

In this tree there are two bottom level events: an integrity failure of the ownship and an area-wide navigation integrity failure. The single ship failure represents an integrity failure of the ownship's on board navigation system. This failure shall occur no more often than 10^{-5} per operation. An area navigation failure is a common mode failure with the target ship, and the same failure will be included in the target ship's fault tree. An area navigation failure affecting both the ownship and target ship is assumed to occur with a frequency that is two orders of magnitude lower than a single ship failure, i.e., with a per operation rate of 10^{-7}. This is consistent with signal in space integrity requirements for GPS WAAS and LAAS. The total of the lead ship's navigation system integrity failure results in a per operation rate of 1.01×10^{-5}. [paragraph taken from ASIA Figure E description]

2.4.1.1.3 Fault tree analysis of Persistent State Vector Error

Figure 11 presents the fault tree for a persistent state vector (SV) error on ownship.

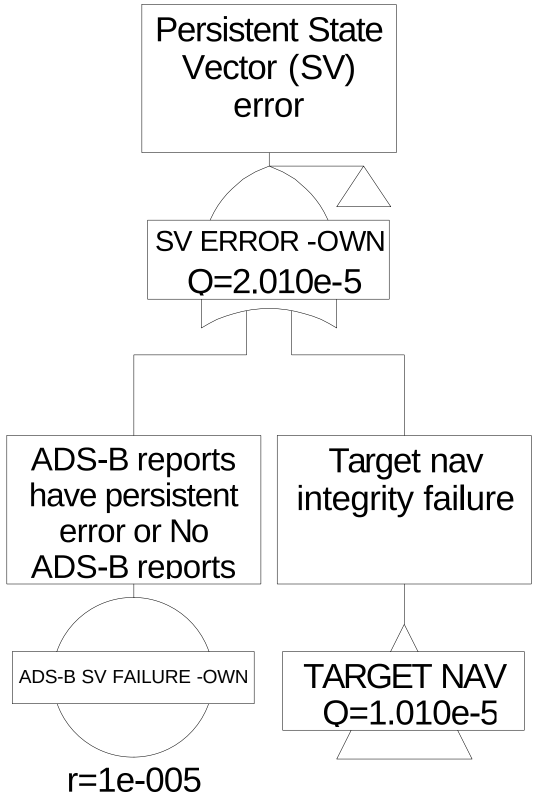


Figure 11: Fault tree of persistent SV error on Ownship

There are two things that can cause a persistent SV error. The first is that the ADS-B reports received from traffic could have a persistent error. A persistent error in the ADS-B messages is presumed to have a probability on the order of 1 in 10^{-5}. Proposed ADS-B messaging and forward error correction coding schemes provide a single message error rate of at least this order, and generally a much higher order. The 10^{-5} value assumes a combination ADS-B hardware and software errors, and error correction coding *[ASIA MASPS Draft]*.

Another reason for a persistent SV error could be an integrity failure of the target's navigation system. The failure of target navigation system mirrors the failure of the ownship navigation system and a fault tree for it is provided in Figure 15.

2.4.1.1.4 Fault Tree analysis of Mitigation failures on Ownship

Figure 12 presents the fault tree for external mitigation methods that could provide conflict resolution.

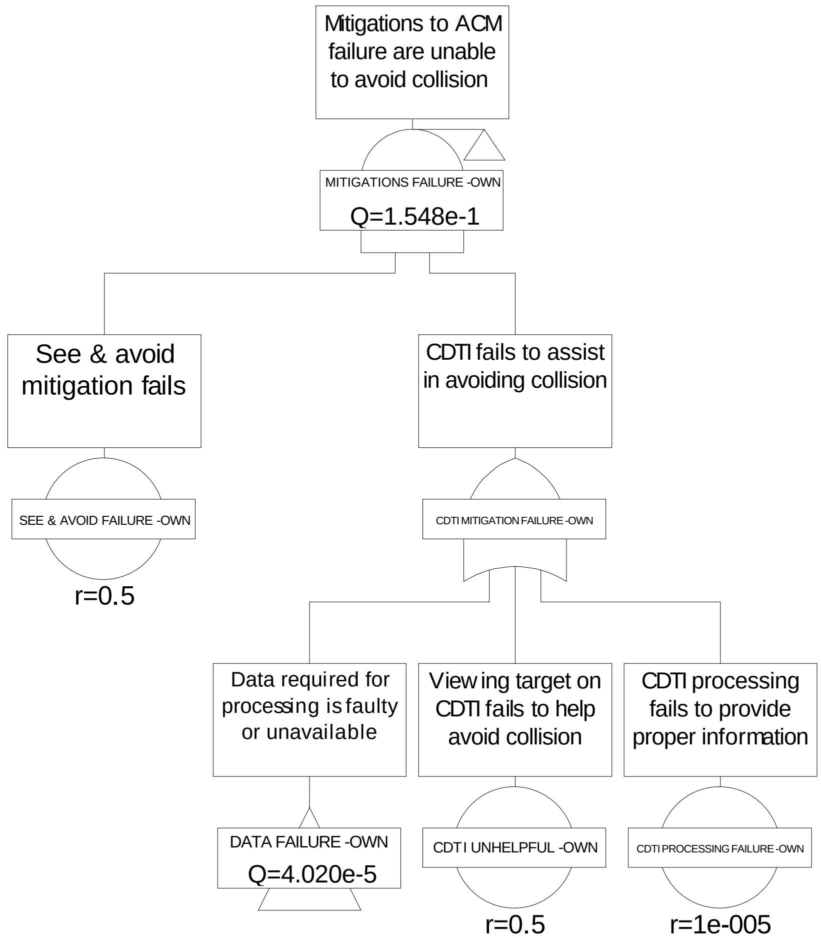


Figure 12: Fault Tree of ACM failure mitigation methods on Ownship

In autonomous airspace there are few if any mitigation methods available for conflict resolution. On the right of the tree a see and avoid mitigation is shown. The failure rate of this operation is set to 0.5 as an approximation to the number of times that see & avoid would actually help avoid a collision.

Another available mean of mitigation is the crew being able to see conflicting traffic on the CDTI and being able to recognize an imminent conflict.

The CDTI mitigation can fail if the data being displayed by the CDTI is faulty, if the CDTI processing function fails to display the right information, if viewing the right information does not provide any assistance to the crew, or if the crew fails to notice the information on the CDTI. The input data failure is a common mode failure that has been discussed in section 2.4.1.1.1.

The ability of CDTI to help the crew avoid a collision is debatable and currently it has been given a failure rate of 0.5. The actual failure rate may be higher.

2.4.2 Fault Tree Analysis of Target Related Failures

As the fault trees for target related failures are identical to the ones for ownship described above, they have been provided below without any additional description.

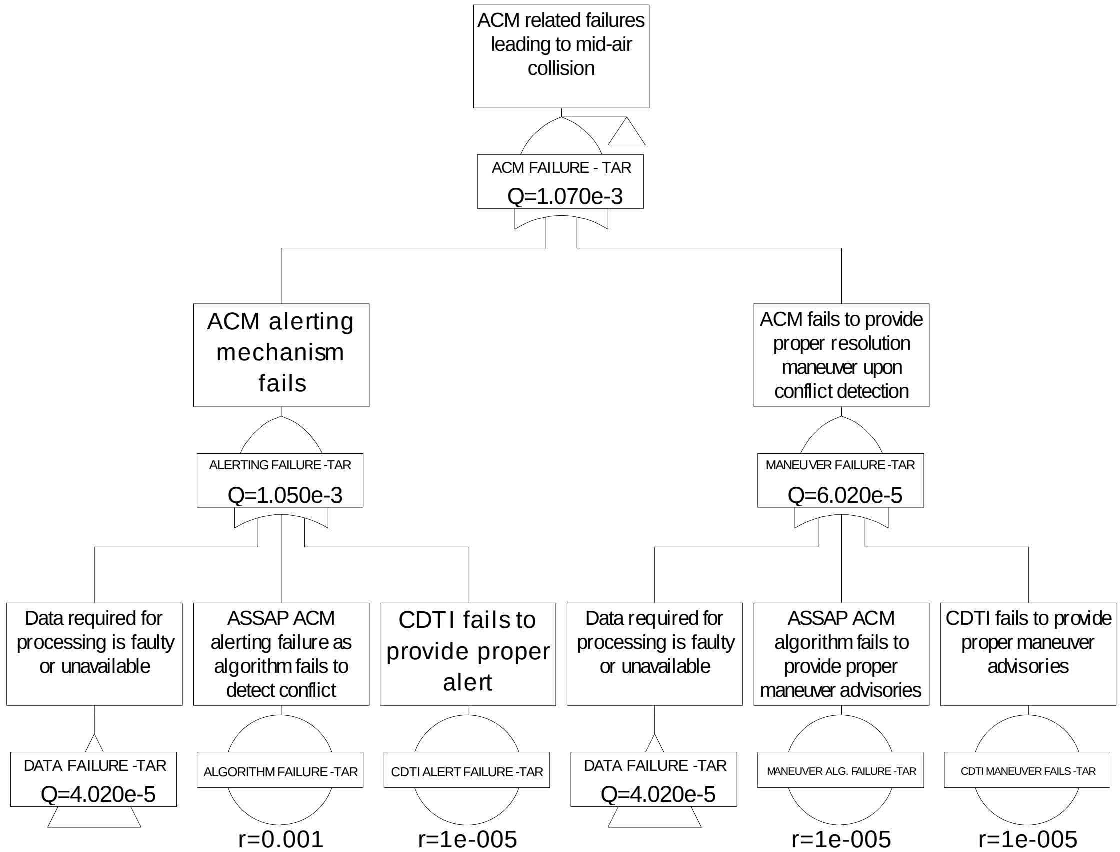


Figure 13: Fault tree of ACM failure on Target

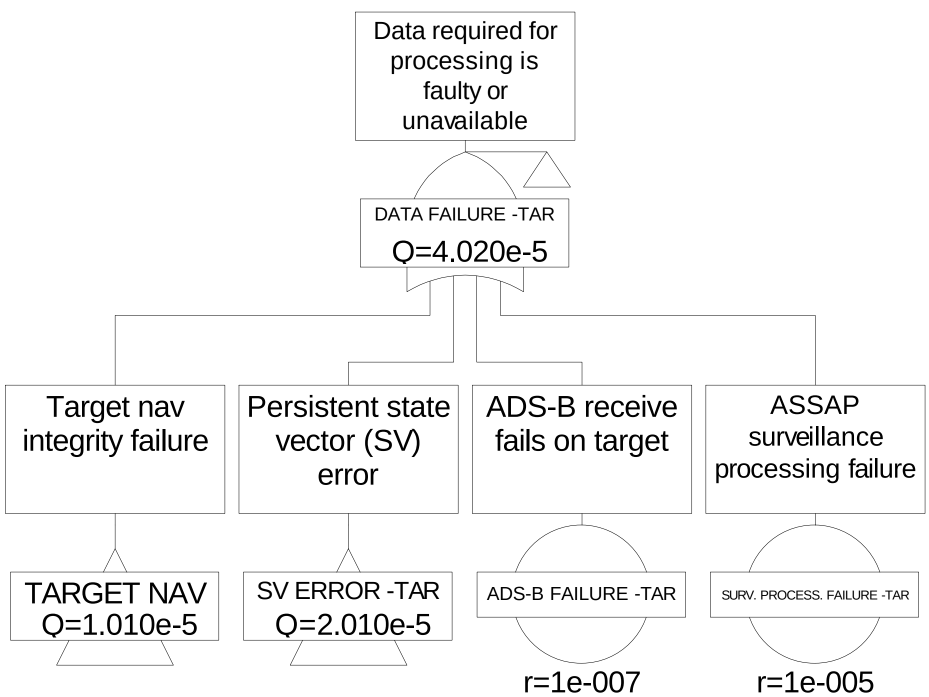


Figure 14: Fault Tree for Data Input error on Target

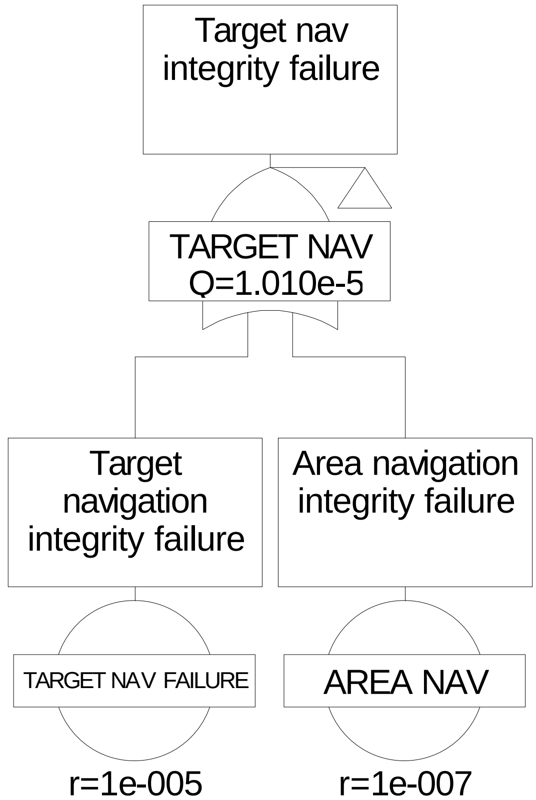


Figure 15: Fault tree of Target Navigation Integrity Failure

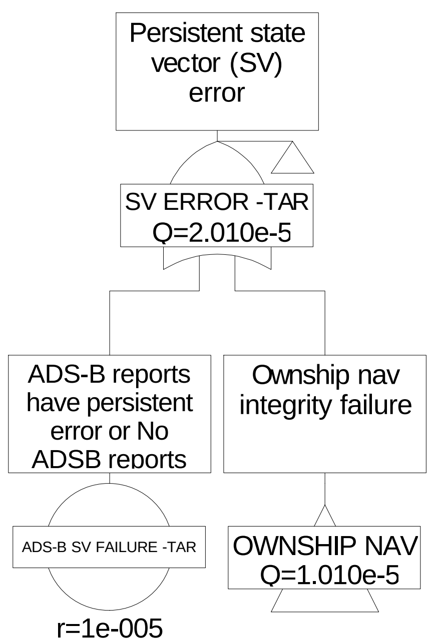


Figure 16: Fault tree of persistent SV error on Target

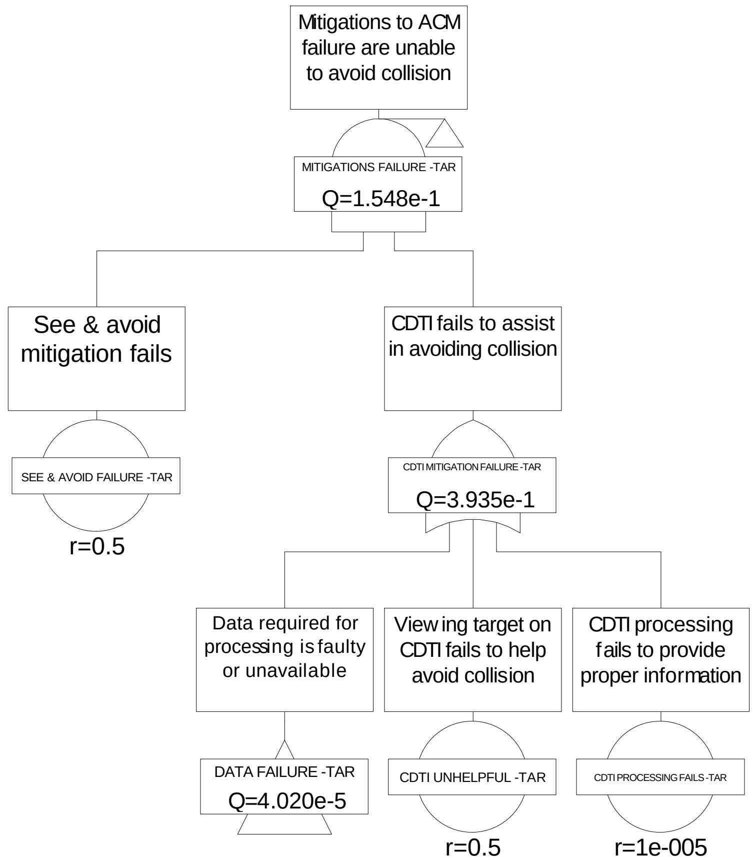


Figure 17: Fault Tree of ACM failure mitigation methods on Target

2.4.3 Summary of Mid-Air Collision Analysis

This section concludes the analysis of mid-air collision in autonomous airspace using ACM. If the bottom level events occur at or below the probabilities listed then the ACM application can keep the number of mid-air collisions to less than 3×10^{-9} per flight hour. This is an acceptable criticality for a mid-air collision encounter.

2.4.4 Discussion of Safety and Operational Requirements related to the ADS-B MASPS (RTCA DO-242A)

2.4.4.1 Introduction

One of the assumptions made in the Monte Carlo simulations described in section 2.5 is that position uncertainty has known integrity bounds. This concept of position uncertainty bounds is present in the ACM Application Description (Section 1) in the definitions of Assured Normal Separation Distance (ANSD) and Assured Collision Avoidance Distance (ACAD). While there could never be absolute bounds on the position error, expected bounds could be established to handle nearly all cases. The ACM Application Description provides the ANSD and ACAD concepts to allow for ACM functionality and interoperability among aircraft with varying navigation system quality. ACM is intended to work with the navigation information available. This is somewhat different from the idea that a minimum system is required for a functional and interoperable system.

The ADS-B MASPS (RTCA DO-242A) describes horizontal position statistics in terms of NAC, NIC, and SIL. This section (2.4.4) describes the relationships between the ACM Application Description and the ADS-B MASPS.

The requirements are summarized below in section 2.4.4.5 and, for convenience, in section 3 as well.

2.4.4.2 Safety Considerations

Unlike other applications, ACM excludes uncertainty buffers from the minimum desired distances between aircraft. The Assured Normal Separation Distance (ANSD) and the Assured Collision Avoidance Distance (ACAD) are independent of the navigation system integrity. The uncertainty is taken into account in the trajectory uncertainty and position uncertainty buffers. Buffer values are set to protect the ANSD.

The NAC (Navigation Accuracy Category) is represented by a radius of estimated position uncertainty *(EPU)* such that the actual position is expected to be within *EPU* of the reported position with a probability of 95%. Allowing the ANSD to be penetrated with a likelihood of 5% is probably not good enough because the distribution of the errors outside the *EPU* is not known. As ACM proves itself over time, the ANSD could shrink to a very small distance (approaching the ACAD) for certain flight operations. One possible consequence of this is that safety credit may not be taken for the ANSD.

Since the NAC distance is not good enough for safety, especially for small ANSD's, the NIC (Navigation Integrity Category) and SIL (Surveillance Integrity Level) values are considered next. The NIC is represented by a radius of containment r_c such that the actual position is expected to be within r_c of the reported position with a probability of 99.9% (SIL=1), 99.999% (SIL=2), or 99.99999% (SIL=3). The NIC would fit the ACM Application Description's concept of position uncertainty if the true position were within the NIC's radius of containment of the reported position so often that the target level of safety is met.

The NIC level does not affect the safety of the system as long as the integrity is known. That is, NIC=0 (unknown integrity) is not acceptable, but NIC=1 (radius of containment of 20 NM) is safe. For practicality rather than safety, a reasonable NIC must be chosen. This is the subject of section 2.4.4.3.

The choices for Surveillance Integrity Level are SIL=1, SIL=2, or SIL=3. SIL=0 (unknown) is not acceptable. Based on the Ownship Navigation Integrity Failure and Target Navigation Integrity Failure fault trees of Figure 10 and Figure 15, setting SIL=2 (10^{-5}) would meet the target level of safety.

2.4.4.3 Navigation Integrity and ACM Utility

Although a Navigation Integrity Category (NIC) of 1 (20 NM radius of containment) is acceptable for safety, it is not practical for ACM. The choice of NIC for ACM is really a matter of judgment, and a small meeting comprising members of RTCA SC-186 was convened to discuss appropriate NIC values. One proposal was to set the NIC based on the Assured Normal Separation Distance (ANSD) desired for particular airspace. In particular, make the radius of containment approximately 10-20 percent of the ANSD. The group considered a two nautical mile ANSD as being appropriate for initial ACM implementations. This set the NIC at 7 with a radius of containment of 0.2 NM.

Other factors, such as wake vortices and overall comfort level, will likely limit the minimum practicable size of the ANSD. Thus, a NIC of 7 is likely to be adequate for any ANSD value.

An installed ACM system may be required to perform at the NIC=7 level. However, in case of degradation in navigation integrity during ACM operations, ACM will continue to function. ACM will use larger position uncertainty buffers as appropriate to maintain (or reacquire) the target level of protection of the Assured Normal Separation Distance.

The Navigation Accuracy Category (NAC) is not a parameter of direct interest for ACM. Any NAC is acceptable as long as the NIC requirement is satisfied. For NIC=7, this means that the NAC will generally be 7 or better (*EPU* less than 0.1 NM).

2.4.4.4 Altitude Reporting Requirements

The ADS-B MASPS (RTCA DO-242A) defines a two-bit quantity called the Barometric Altitude Quality (BAQ) code. All equipment conforming to the MASPS sets the BAQ to zero, so the BAC code does not provide any information. However, ACM requires altitude integrity and containment information.

The integrity requirements for altitude information follow the same principles as those for lateral position reports. Safety is not compromised if the altitude uncertainty is large, but ACM does require bounds on that uncertainty.

Because there is no required broadcast of barometric altitude quality at this time, minimum altimetry requirements for ACM must be established. If altimetry requirements better than those established for ACM are imposed by other applications and supported by future versions of the ADS-B MASPS, ACM can work with those requirements as long as the 10^{-5} integrity bounds are known.

To establish the vertical containment bounds, five topics are discussed in sections 2.4.4.4.1 through 2.4.4.4.5 below. Some of the analyses that supported the standards for Reduced Vertical Separation Minimum (RVSM) equipment and operations can be applied to the ACM application. RVSM is discussed in section 2.4.4.4.1. Section 2.4.4.4.2 describes the use of existing altimetry equipment and nominal vertical separation distances. Section 2.4.4.4.3 describes adding integrity augmentation to existing systems. Sections 2.4.4.4.4 and 2.4.4.4.5 are similar. In section 2.4.4.4.4 the ADS-B message contains a code to indicate that minimum requirements are met. In section 2.4.4.4.5 a more extensive table is used, patterned after the NIC and SIL tables for lateral position containment and integrity.

The options for establishing ACM altimetry requirements are summarized in section 2.4.4.4.6.

GPS-based altimetry with integrity was considered, but altitude integrity bounds are defined only for NIC=9 or better. In general, the GPS integrity bounds are only available when the Wide Area Augmentation System (WAAS) is available. Nominal ACM performance should be available even in areas not served by WAAS. RVSM-equipped aircraft can likely satisfy the ACM altimetry requirements, although RVSM is not required. ACM could use larger vertical containment bounds than RVSM as long as the appropriate integrity level is satisfied.

2.4.4.4.1 Reduced Vertical Separation Minimum (RVSM)

Aircraft in airspace between FL290 and FL410, inclusive, have traditionally been flown with 2000 feet of nominal vertical separation. Reduced Vertical Separation Minimum (RVSM) equipment and operational procedures have been developed to reduce the nominal vertical separation to 1000 feet. RVSM-equipped aircraft are now flying in these flight levels in some parts of the world. With RVSM, adjacent flight levels can be assigned, significantly increasing the capacity of the high altitude en route system.

RVSM capability is achieved by requiring two independent altitude measurement systems, an altitude-reporting transponder, an altitude alert system, and an automatic altitude control system. The equipment performance must meet the new standards for RVSM operation that include a system integrity of 10^{-5} per flight hour.

The RVSM height-keeping performance specifications are given in Table 5, below. The total vertical error must be below the requirement curve plotted in Figure 18. The plot shows that the probability of the total vertical error exceeding about 460 feet is no more than 10^{-5}. The probability of the total vertical error exceeding approximately 400 feet is no more than 10^{-4}.

Total Vertical Error (TVE) in feet	Probability of Exceeding TVE
> 300	$< 2 \times 10^{-3}$
> 500	$< 3.5 \times 10^{-6}$
> 650	$< 1.6 \times 10^{-7}$
950-1050	$< 1.7 \times 10^{-8}$

Table 5: RVSM Height-Keeping Performance Specifications. Guidance taken from ICAO 9574.

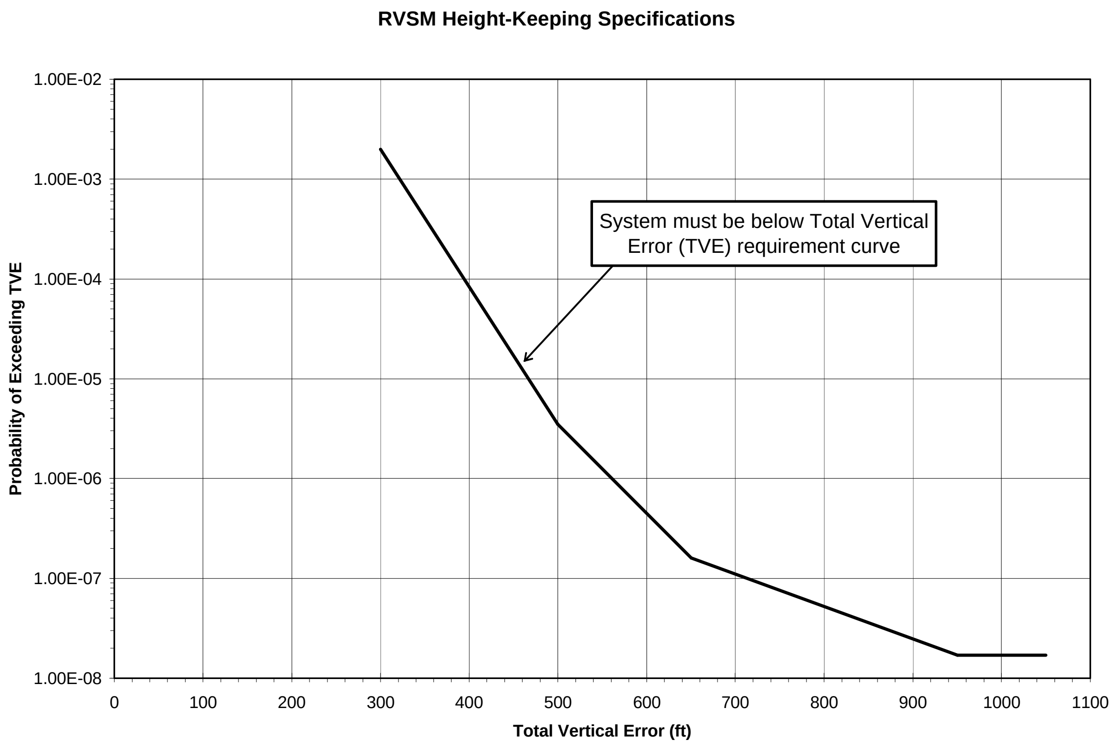


Figure 18: Total Vertical Error specification for RVSM.

RVSM safety analysis results have been presented in, "The EUR RVSM Pre-Implementation Safety Case," Eurocontrol RVSM 691, Version 2.0, 14 August 2001. In practice, RVSM is meeting the target level of safety. Safety credit is taken for the fact that aircraft on adjacent flight levels only occasionally have horizontal overlap. Also, air traffic control is involved in assigning flight levels. ATC involvement improves safety in the RVSM environment.

The study found that flight level busts are not tolerable and reduce the overall safety to something below the target level of safety. Since RVSM requires an automatic flight level capture or acquisition feature, the frequency of level busts is expected to decrease. The mitigations against level busts are assumed to be sufficient to ensure that their occurrence is at least as manageable in the RVSM airspace as in the current 1000-foot environment below FL290.

In conclusion, RVSM is a safe system in the flight levels and operational environment for which it was designed. Although the altimetry requirements for ACM are somewhat different, elements of RVSM and the RVSM analyses can be used to establish achievable requirements for ACM.

2.4.4.4.2 Use of Existing Altimetry Equipment

The simplest proposal for ACM altimetry requirements is to use existing altimetry equipment and existing nominal vertical separation values. The approach is probably not acceptable because it does not, in general, meet the integrity requirements that resulted from the fault tree safety analysis. If this approach were adopted in the current environment, then the system would be as safe as today's system. However, in autonomous ACM airspace where all aircraft are equipped with ACM and the aircraft maintain their own separation from one another without the benefit of air traffic control, the level of safety would be reduced from today's level.

Another option is to use the current altimetry equipment but abandon the 1000-foot nominal vertical spacing. This would require using an analysis of existing systems and establishing a containment bound that meets the required 10^{-5} per flight hour integrity. This would be acceptable only if it is shown that the altimetry systems in use today are, in general, capable of achieving the required level of integrity.

2.4.4.4.3 Use of Existing Altimetry Equipment with Integrity Augmentation

It may be possible to use existing altimetry equipment and specify a means of checking the output to improve integrity. One possible implementation is to use GPS, outside air temperature sensors, and perhaps other sensors to estimate pressure altitude. This estimate could be compared to the measured pressure altitude and potentially improve the overall integrity. This may be less expensive than a full RVSM system, but the result would likely have larger vertical containment bounds than what is achievable for RVSM.

The integrity improvement and containment bounds are not known. Quantifying these parameters would be possible only after completing development and analysis work. This potential solution does not offer an immediate basis for setting the ACM altimetry requirements.

2.4.4.4.4 Establish a Minimum Requirement for Barometric Altitude Quality

One potential solution is to establish a specific integrity requirement and containment bound for altitude reports. This could be done within the existing framework of the ADS-B MASPS, DO-242A. Currently the 2-bit Barometric Altitude Quality (BAQ) field is set to 00. One or more of the available BAQ bit combinations could be defined to indicate the altitude integrity and containment bounds. All aircraft equipped with ACM would be required to meet the established integrity and containment requirements, and the BAQ would be broadcast to indicate to others that the altimetry system meets the minimum requirements to support ACM.

By examining the performance and altitude measurement capabilities of the current fleet of aircraft, by learning from the parallels between needed ACM requirements and established RVSM requirements, and by considering the quality of achievable lateral spacing, engineering judgment may be applied to establish reasonable altimetry requirements for ACM-equipped aircraft. One proposal is to require that the true barometric altitude must be within *x* feet of the reported barometric altitude 99.999% of the time (referenced to a flight hour). If

GPS-based altitude is used, the true geo-referenced altitude must be within *x* feet of the reported altitude 99.999% of the time.

The containment being proposed is subject to analysis and industry consensus. For RVSM, the total vertical error (with 10^{-5} integrity) is no more than about 460 feet. Of that 460 feet, 65 feet is allocated to the tolerance of the automatic altitude control system. That leaves about 400 feet for other errors. For aircraft not using or not equipped with an altitude hold autopilot, the altitude keeping tolerance should be increased to at least 200 feet. As most aircraft will not be equipped with altimetry systems meeting the stringent RVSM requirements, an additional tolerance should be included, likely on the order of 200 to 300 feet. Overall, then, there would be a total vertical error of at least 800 to 900 feet, with an integrity of 10^{-5} per flight hour.

A typical vertical ANSD (See section 1.2.1.2.) may be on the order of 500 feet. With containment set at plus or minus 800 feet, the low end of the range of total vertical errors discussed in the previous paragraph, aircraft could fly with nominal vertical separations of 2100 feet. This minimum 800-foot value does not support 2000 foot nominal vertical separations. One proposal is for a more conservative 1200-foot containment to allow a broader range of aircraft to equip for a reasonable cost. When combined with a 500-foot ANSD, plus or minus 1200 feet of total vertical error (with 10^{-5} per flight hour integrity) would enable two ACM-equipped aircraft in level flight to very safely occupy nominal altitudes separated by 3000 feet.

ACM could require one of the BAQ code combinations to represent 10^{-5} per flight hour integrity and the associated containment bound. This is the recommended solution. If another application assigns values to one of the remaining BAQ codes that are more stringent than the minimum required for ACM, then ACM could take advantage of that and permit closer nominal vertical spacing.

The containment bound should be set to a single specific parameter, probably in the range of plus or minus 800 to 1200 feet. This solution does not offer as much accommodation for varying aircraft equipage as the method of section 2.4.4.4.5, but this solution is preferred because it does not require a major change to the ADS-B MASPS.

2.4.4.4.5 Establish ADS-B Requirement for Broadcast of Barometric Altitude Quality

The ADS-B MASPS could be modified to include NIC(altitude) and SIL(altitude) tables, analogous to the current NIC and SIL tables for horizontal navigation performance. (NIC is Navigation Integrity Category and SIL is Surveillance Integrity Level.) An ADS-B message would report the altitude category and ACM would use the associated containment bounds in its calculations. ACM would require a SIL(altitude) corresponding to 10^{-5} per flight hour. ACM would use the vertical containment value corresponding to whatever NIC(altitude) was being reported. However, ACM would require that the containment parameter be at least as good as some specified value. That value would likely be plus or minus 800 to 1200 feet as established in section 2.4.4.4.4 above. This approach allows ACM to take full advantage of a range of acceptable altimetry capabilities. Aircraft that are equipped to fly with reduced vertical separation would be enabled to do so.

2.4.4.4.6 Summary of Options for Altitude Reporting Requirements

The options for establishing ACM altitude reporting requirements are summarized in Table 6 below.

Section No.	Option	Comments
2.4.4.4.1	Reduced Vertical Separation Minimum (RVSM)	RVSM-equipped aircraft would likely meet ACM altimetry requirements. However, requiring RVSM on all ACM aircraft is not practical. RVSM has been well analyzed and provides strong guidance for establishing ACM altimetry requirements that are practical and achievable for most aircraft in the fleet.
2.4.4.4.2	Use of Existing Altimetry Equipment	Probably not adequate in autonomous ACM airspace.
2.4.4.4.3	Use of Existing Altimetry Equipment with Integrity Augmentation	This has the potential to be the least expensive and most accessible option, but only if a specific method of augmentation is found that can raise the integrity of most existing altimetry systems to acceptable levels.
2.4.4.4.4	Establish a Minimum Requirement for Barometric Altitude Quality	**This option was selected** because it requires few changes to the ADS-B MASPS. The requirement would be for 10^{-5} per flight hour integrity and a specific vertical containment value that would likely be established as a number in the range of plus or minus 800-1200 feet.
2.4.4.4.5	Establish ADS-B Requirement for Broadcast of Barometric Altitude Quality	This is also a very acceptable option. It allows aircraft with better-than-required altimetry systems to take advantage of their equipment. ACM would permit reduced nominal vertical spacing for better equipped aircraft. The disadvantage is that implementing this option would require more significant changes to the ADS-B MASPS.

Table 6: Summary of Options for Altitude Reporting Requirements

2.4.4.5 Summary of ACM Requirements Related to ADS-B MASPS Parameters

Section 2.4.4 establishes the ACM requirements related to the ADS-B MASPS (RTCA DO-242A) parameters. In particular, the Navigation Integrity Category (NIC) must be 7 or better, corresponding to a horizontal radius of containment of

0.2 NM or smaller. The corresponding Surveillance Integrity Level (SIL) must be 2 or better, indicating an integrity at least as good as 10^{-5} per flight hour. SIL applies to the integrity of the horizontal position, but the same integrity is required for the vertical position. The Barometric Altitude Quality (BAQ) must be defined to indicate that the altimetry report has an integrity level of 10^{-5} per flight hour or better, bounded by some vertical containment value that is yet to be agreed upon. The vertical containment bound will be a fixed minimum value, perhaps in the range of ±800 to 1200 feet. These requirements for nominal performance of installed equipment do not preclude the use of the ACM application in operational cases of degraded performance as long as the level of degradation is known and the system is able to maintain the target level of safety. For example, if the primary navigation system fails and an aircraft reverts to a secondary system with a NIC value of less than 7, ACM will work to maintain or regain the necessary separation.

The requirements developed in this section are included in Table 40 in Section 3.

2.5 ACM Modeling and Monte Carlo Analysis

2.5.1 Executive Summary

Monte Carlo analysis of state-vector-only (i.e. no use of trajectory intent information) ACM (Airborne Conflict Management) was performed on a variety of conflict scenarios. More than a half million simulation runs were performed, examining the effects of equipage, piloting attentiveness, alert response time, turbulence, ADS-B broadcast interval, desired spacing, conflict configuration, and position and velocity errors on the degree of resolution. The simulations utilized relatively conservative values for ADS-B and aircraft performance.

The results suggest that turbulence is the greatest factor affecting the resolutions, followed by the ADS-B broadcast interval, and the time that the pilot takes to respond to the alarm. The probing analysis found that:

- State-vector-only ACM is feasible for self-separation in all but extreme turbulence so long as a) the ADS-B update rate is 12 per minute or better at close ranges and b) pilots respond to conflict alerts within 10 seconds. In this context, self separation means maintenance of the Assured Normal Separation Distance (ANSD). See Figure 2.
- State-vector-only ACM is useful for collision avoidance even in extreme turbulence, poor pilot response time, and long ADS-B update intervals. Here, collision avoidance means maintenance of the Assured Collision Avoidance Distance (ACAD). See Figure 1.
- Position error has negligible impact on the degree of conflict resolution so long as the broadcast error bounds are equal to or larger than the actual error.
- Velocity errors up to 7 knots horizontal and 25 fpm vertical have negligible impact on achieved conflict resolution.
- Ordinary diligence in responding to conflict alerts and to resolution guidance is sufficient. Delays of up to 10 seconds in reacting to a conflict alarm and “flight direction updates” as few as 12 per minute were satisfactory in the scenarios tested.

Note: ADS-B update periods and pilot response times are less critical for conflict avoidance (maintaining separation) than for collision avoidance.

2.5.2 Introduction

2.5.2.1 Goals

The purpose of the work described herein is a “probing” analysis of the Required Surveillance Performance (RSP) for “Free Flight” ACM systems. The “probing” to be accomplished is:

a) verify that ACM is feasible; i.e. demonstrate practical conflict alerting and conflict resolution algorithms

b) quantify the utility/success of ACM algorithms and maneuvers in a variety of “typical” free flight conflict scenarios

c) describe and/or quantify the various surveillance and piloting performance parameters necessary to achieve (a) and (b).

2.5.2.2 Methodology

The basic tools of the investigation are a) a conflict alerting algorithm developed specifically for this work, b) a previously developed conflict resolution algorithm, c) a previously developed free flight simulation system, and d) a random conflict generator developed specifically for this work.

With these tools, a Monte Carlo analysis of Free Flight encounter scenarios could be performed. A total of six encounter types was investigated, with each type being subdivided into three categories according to the maneuvering aircraft: one, the other, or both. For each subcategory, 10,000 random encounter scenarios were created.

The following sections describe the tools, models, scenarios, and assumptions used in performing the work.

2.5.3 Modeling

2.5.3.1 Aircraft Performance Model

The flight model is simple, but sufficient for the testing being performed. The flight model is 3-dimensional, meaning that yaw, roll, and pitch are not directly modeled. The model applies independent maximum accelerations and minimum and maximum velocities in the horizontal and vertical dimensions.

The model's greatest limitation is the lack of roll (bank angle) effects; the lack of roll angle modeling has the following effects:

- Whereas real aircraft reach maximum lateral acceleration over a period of time as the bank angle increases, the simulator's flight model allows maximum lateral acceleration to be achieved instantly.
- Whereas the maximum lateral acceleration is greater than the maximum longitudinal acceleration for virtually all aircraft, the simulator uses the same value for both.

For the purposes of the current investigation, these limitations have a very simple, very conservative solution. By limiting horizontal acceleration to 0.1[2] Gs a) maneuvering limits are extremely conservative, b) the effect of roll rate is limited by the small degree of roll, and c) differences between maximum longitudinal and lateral acceleration are rendered moot since neither acceleration limit is met.

2.5.3.2 Turbulence Model

One of the key components necessary to test ACM algorithms is the addition of 'noise' to the flight trajectories that will cause the projected positions and distance at the time of projected point of closest approach to vary even as the aircraft involved in the conflict attempt to maintain smooth, constant trajectories.

[2] 0.2 Gs maximum lateral acceleration was utilized in the "close maneuvering" scenario.

To accomplish this goal, a turbulence model has been added to the simulator. The model is based on the Dryden atmospheric turbulence model[3].

2.5.3.2.1 Model Design

The Dryden model uses a Gaussian distribution of pseudo-random numbers passed through a filter to produce a specific frequency spectrum. Quoting from the paper:

> *"The basic assumptions are that the atmospheric turbulence is uniform, it is isotropic at least horizontally, and the turbulence velocity follows the Gaussian distribution….The results obtained are applicable to flights along any path at medium and high altitude (above [approx. 2000 feet]) and flights along horizontal path at low altitude. A non-horizontal flight at low altitude can be treated in sections."*

The algorithm uses a small set of variables:

1) Physical scale of the turbulence; in a sense, the average or RMS "wave length" of the turbulence. Typical value: 530m or roughly 1/3 of a mile.

2) RMS gust velocity: 1.5 m/s or approximately 4 knots.

3) The aircraft velocity

4) Euler front-differencing parameters P and Q which perform the filtering on the random Gaussian input signal such that

   $$x_i = Px_{i-1} + Qs_i$$

   where:

   x_i = current velocity

   x_{i-1} = previous velocity

   s_i = psuedo-random Gaussian input signal

   $P = e^{-v\Delta t/L}$

   $Q = s \times \sqrt{1 - e^{-2v\Delta t/L}}$

   v = aircraft velocity (lateral and vertical turbulence)

   $v' = \sqrt{3}$ times aircraft velocity v (longitudinal turbulence)

   Δt = time interval (e.g. 0.1 seconds)

   L = turbulence scale (e.g. 530 m)
   but limited to aircraft's altitude for vertical turbulence

   σ = turbulence intensity -- RMS turbulence speed (e.g. 1.5 m/s)

The implemented model does *not* diminish turbulence with changes in altitude:

1) Low turbulence scenarios are still tested because the Monte Carlo-specified turbulence ranged all the way down to none.

2) This is a very conservative assumption.

3) The assumption eliminates artifacts that may be associated with an improper model of how turbulence varies with altitude.

---

[3] As described in NASA report TT-20342, "A Digital Simulation Technique for the Dryden Atmospheric Model" which is a translation of a paper published in the Chinese, "Acta Aeronautica et Astronautica Sinica, Vol. 7, No. 5, Oct. 1986 pp 433-443.

2.5.3.2.2 Model Results

Figure 19 displays characteristic output from the turbulence model. Note that the maximum velocities are considerably higher than the 1.5 m/s RMS velocity. Note also that the velocity variations experienced within the aircraft will be considerably less than the velocity differences in the local wind field. This is because the acceleration experienced by the aircraft is a function of the wind field, the mass of the aircraft, and the effective surface area of the aircraft in the direction of the wind. With respect to vertical turbulence, for example, the rate at which the aircraft velocity approaches the local wind field velocity will be largely a function of the wing loading, with sailplanes being much more affected by turbulence than a heavily loaded fighter aircraft.

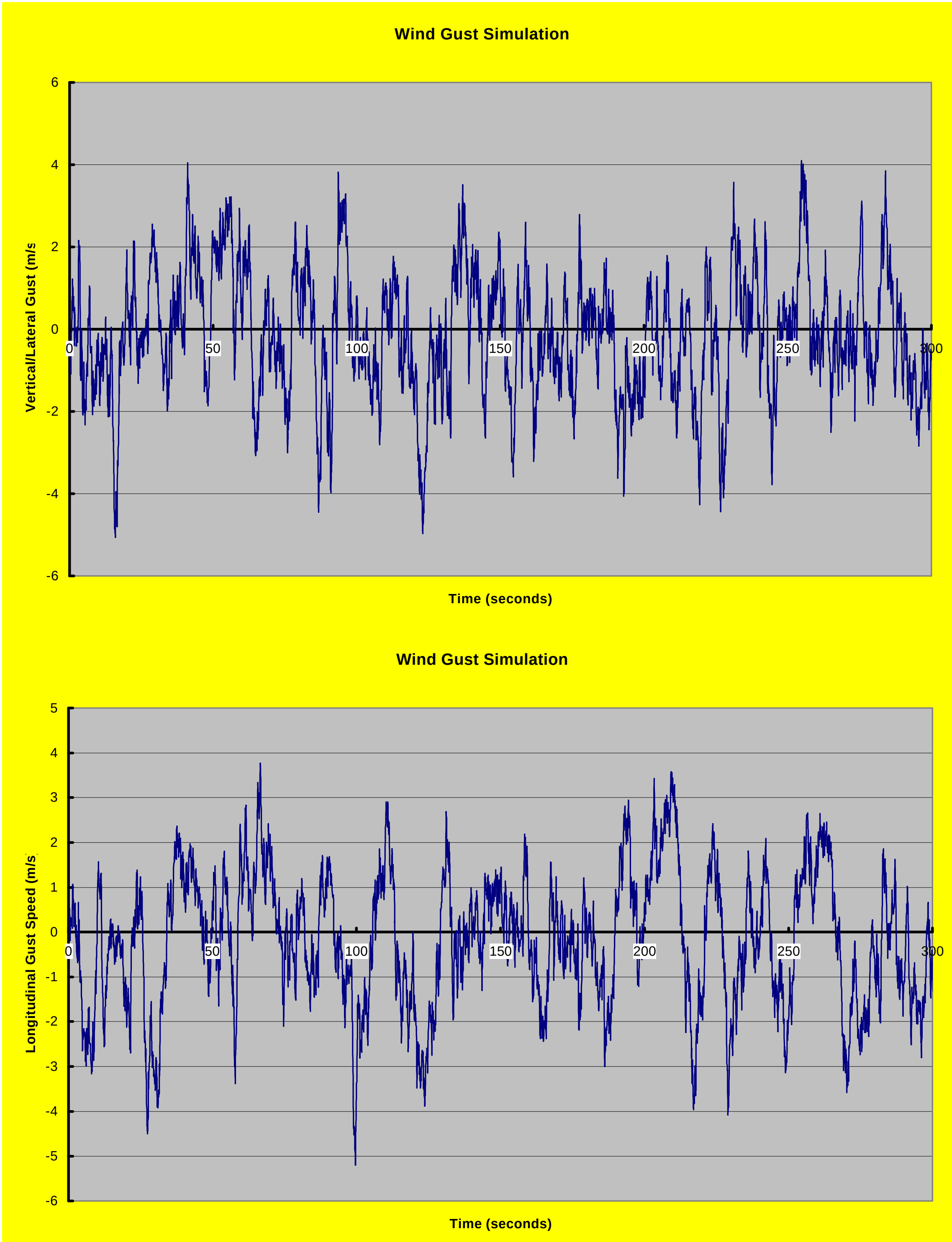


Figure 19: Output of the turbulence model. Above: lateral/vertical speed. Below: longitudinal speed. Note that the longitudinal 'frequency' is somewhat smoother since the higher mass/drag ratio in that direction damps higher frequency variations.

2.5.3.3 Wind Field Model

The simulator does not currently support a wind field model. The inclusion of a wind field model in the current study would serve no purpose since no intent or time-of-arrival information is exchanged/utilized and the state vectors which are exchanged are absolute rather than wind field-relative.

2.5.3.4 Pilot/FMS Model

The aircraft controller model may be thought of either as a pilot or an FMS system. The behavior modeling is simple, but sufficient:

2.5.3.4.1 Goal Seeking:

The pilot/FMS model has flight path "goals," points on a predetermined route that the aircraft attempts to reach, in order. The immediate goal is dropped and the next goal pursued when the aircraft is sufficiently close to the immediate goal that the turn to the next goal will leave the aircraft on a trajectory overlying a line drawn between the immediate goal and the next goal.

There is no logic specific to maintaining a particular ground track or flight level; rather, the pilot/FMS seeks, in the absence of any conflict alert, only to fly the most direct trajectory from the current position (whatever that might be) to the next goal position. Hence, an aircraft which has deviated from its original trajectory due to turbulence or a conflict resolution maneuver does not attempt to return to the original course, but instead always seeks to travel the shortest distance from its current position to the next goal position.

2.5.3.4.2 Update Interval

The pilot/FMS redirects the flight of the aircraft at an interval averaging between 2 and 5 seconds as determined by the Monte Carlo conflict generation. The same update interval parameter applies to all aircraft in a particular simulation. There is, however, a further randomization of the interval between individual updates which adds or subtracts up to 20% of the base period.

2.5.3.4.3 Alert Response

When a conflict alert is issued, a 'pilot alarm delay' period begins. During this period, the simulated pilot/FMS continues to be concerned only with flying to the next goal point. After the period has elapsed, the pilot/FMS, on subsequent update intervals, directs the aircraft according to the then-current ACM resolution until the conflict is resolved. In the event that the alert is not continuous, the pilot alarm delay is *not* reset. The pilot alarm delay is not reset in this case because it is the initial alert that makes the pilot aware of the conflict and causes him to consider/prepare for resolution maneuvering.

While the simulator includes the ability to model a delay in pilot actions, the feature was not utilized in the current study. The assumption is that the pilot will, after the alarm delay interval, be attentive and responsive to the resolution advisory.

2.5.3.5 ADS-B Model

Table 7 lists the various ADS-B data fields and how/if they were incorporated into the simulation.

Time of Applicability	Included in message, utilized in ACM calculations.
Identification	ADS-B messages indicated the unique aircraft from which they were broadcast. There was no implementation of ADS-B Emitter Category (a field which identifies the type of the emitter, e.g. light aircraft, sailplane, etc.) as the algorithms made no use of the information.
A/C Length and Width Codes	Not implemented. Accommodation of the aircraft's size is assumed to be included in the minimum separation specification.
Position	Only geometric position was supported/utilized by the simulation. The simulation utilized a Cartesian coordinate system of meter measurements rather than lat/lng referenced to the WGS-84 ellipsoid. The granularity of the position values, however, closely approximated those of ADS-B position reports and the choice of coordinate system should not play a role in the effectiveness of ACM. The granularity was 0.0012 miles (about 6 feet).
ADS-B Position Reference Point	Not implemented. Accommodation of the reference point position is assumed to be included in the minimum separation specification.
Altitude.	Only geometric altitude is implemented/utilized. The granularity was 25 feet.
Horizontal Velocity	Only ground-referenced horizontal velocity is implemented/utilized. The implementation was through separate N/S and E/W velocity components, each with a 1 knot granularity.
Vertical Rate	Implemented. Utilizes geometric vertical velocity. Granularity was 64 fpm.
Heading	Implemented. Utilized geometric heading.
Capability Class.	Not implemented. ACM system assumes other aircraft is not equipped and/or will not maneuver to resolve conflicts.
Operational Mode.	Not implemented.
Navigation Integrity Category	Not implemented..
Navigation Accuracy Category for Position	Bounding of position error was implemented not as a category but as two distance-in-meters values. As the simulation already includes randomization of actual error vs. reported error bounding (with the actual always less than the bounds) the 'overstating'/conservative nature of category-style error bounds is well modeled.
Navigation Accuracy Category for Velocity	Handled in the same fashion as NAC for Position.
Surveillance Integrity Level	Not implemented. The error bounds were utilized "as is".
Barometric Altitude Quality Code	Not implemented.
Barometric Altitude Integrity Code	Not implemented.
Emergency/Priority Status	Not implemented.
Intent Information.	Not implemented. This simulation investigated the simplest utilization of ACM – use of the state vector only. Note: The ADS-B MASPS assumes that intent information will be available (and is required?) for the longer-range ACM functions. Our findings are that intent information is not required in order to maintain separation, but is likely useful as a means to minimize nuisance alerts.

Table 7: ADS-B Data Utilization

2.5.3.6 Radio Model

2.5.3.6.1 Reception Range/Probability

The radio reception model has reliability fall off with the cube of the lateral distance:

$$Prob_{recv} = 1 - (dist_{XY}/dist_{MAX})^3$$

For the purposes of the current tests, $dist_{MAX}$ was fixed at 90 NM. No other ADS-B reception failures/drop-outs (e.g. receiver failure) were modeled.

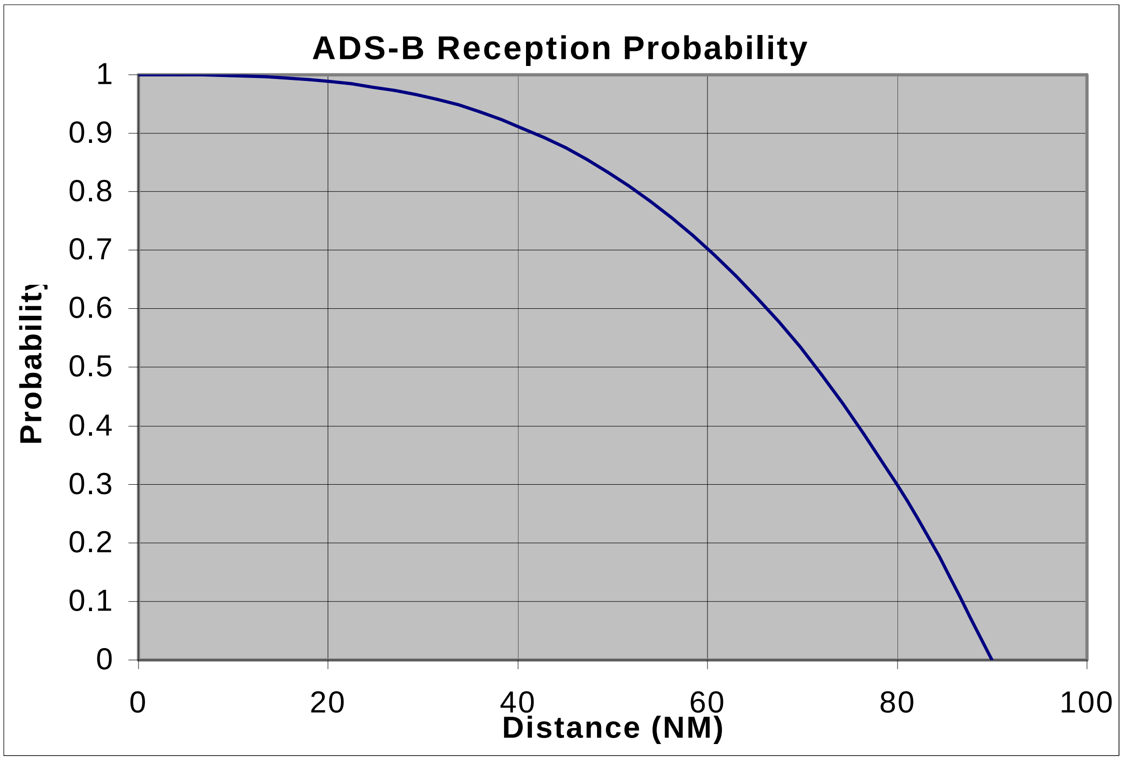


Figure 20: ADS-B reception rate as a function of tx/rx distance.

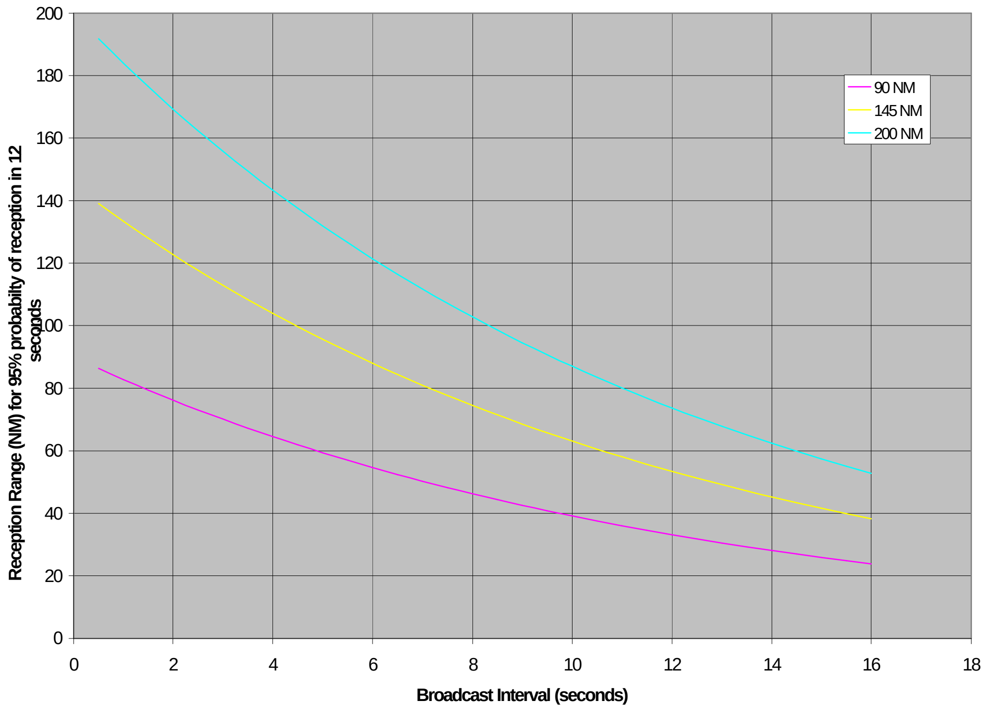


Figure 21: Distance vs. Interval curves for 95% probability of reception in 12 seconds for individual reception probability ($1 - (d/x)^3$) for x values of 90, 145, and 200 NM. Example: Using the 145 max reception range and a broadcast interval of 4 seconds, we find that there is a 95% probability of receiving a broadcast within 12 seconds at a range of 103 NM.

2.5.3.6.2 Broadcast interval

The average broadcast interval was a parameter of the Monte Carlo randomization. The *actual* interval between individual ADS-B broadcasts then varied from the average by a random amount up to a specified maximum. For the purposes of the current research, the interval randomization was 20% of the median value. Hence, if the Monte Carlo simulator determined that the average update interval was to be 12 seconds, the actual interval between broadcasts varied randomly between in a range between 9.6 and 14.4 seconds.

2.5.4 Conflict Alerting Algorithm

The alerting algorithm utilized in this testing is one previously developed by Rockwell Collins and is proprietary. In general terms, the algorithm developed attempts to measure three parameters of a developing conflict. These are the magnitude of the projected conflict, the certainty of the conflict, and the time until the conflict occurs. The determination of when the CD alert is presented to the pilot is a function of the magnitude and certainty and an inverse function of the time until the conflict begins. More directly, severe, certain, conflicts occurring very soon will likely be annunciated while an improbable, minor conflict far in the future will probably not be annunciated.

Parameter	Description
Magnitude	The size or degree of the predicted conflict is a measure of how close the aircraft are projected to pass to each other relative to the desired separation.
Certainty	The degree of confidence that a conflict will actually occur. This is determined using a running, weighted ‘average’ of conflict projections over a period of time where the input to the average is ‘1’ during intervals over which the state vectors project a conflict and ‘0’ during intervals where they do not.
Timing	The time remaining until loss of separation occurs. The value of this parameter tends to be more stable than the others, particularly at large distances.

Table 8: Parameters utilized in the Conflict Detection algorithm

The relative effectiveness of the alerting algorithm is represented in Figure 22 and Figure 23. In Figure 22 the algorithm is applied against a set of randomly generated head-on approaches with plots presenting the relationship between the hazard level (the degree to which the protected zone was violated) to the alert time (number of seconds prior to the start of the violation). A negative hazard number indicates that the protected zone was not violated. There are separate plots for light, medium, and heavy turbulence as well as a summary plot. As one would expect, the warning time tends to increase with the severity of the conflict and to decrease with increasing turbulence. The nuisance alarm rate also increases with increasing turbulence (since turbulence has the effect of lowering the signal-to-noise ratio of the conflict detector).

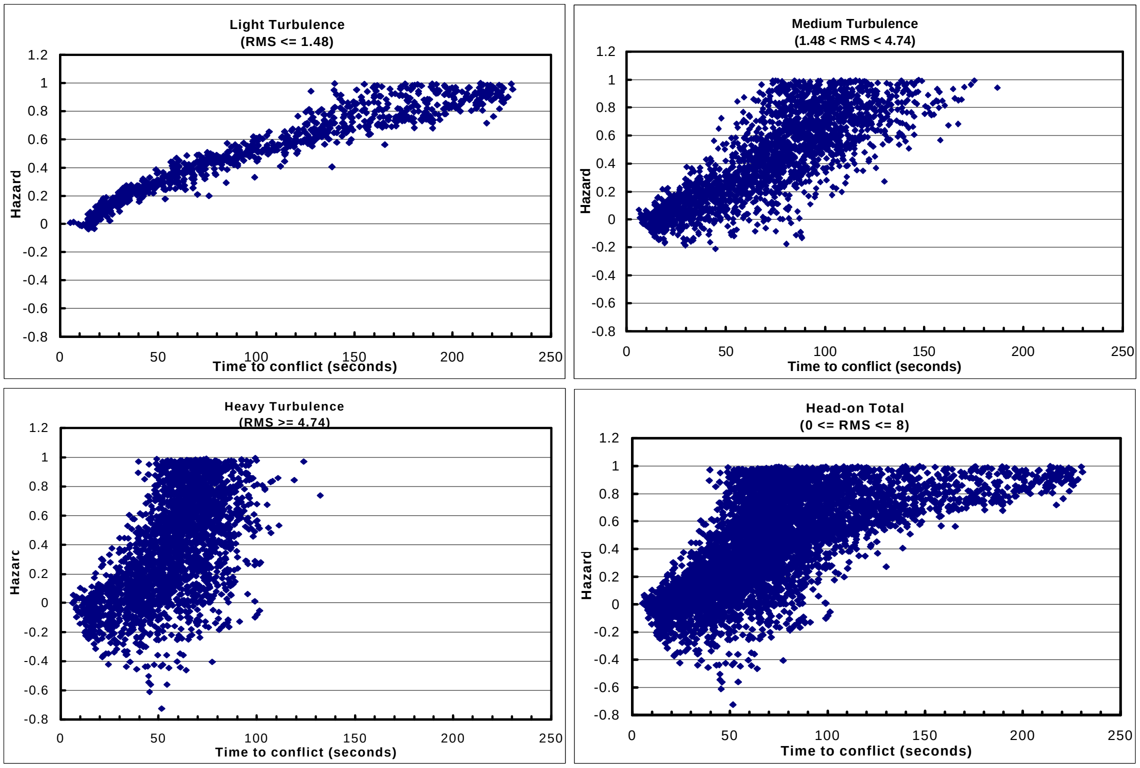


Figure 22: Alert-time vs. hazard (degree of intrusion) for head-on aspect at various levels of turbulence: light (top left), medium (top right), heavy (bottom left), and combined (bottom right).

Figure 23 illustrates the nuisance alarm rate for the head-on conflicts as a function of the hazard level for the three levels of turbulence and the totals. Note that even in the case of heavy turbulence (ranging as high as 8 knots RMS) the nuisance alarm rate is small or zero for all but the nearest misses.

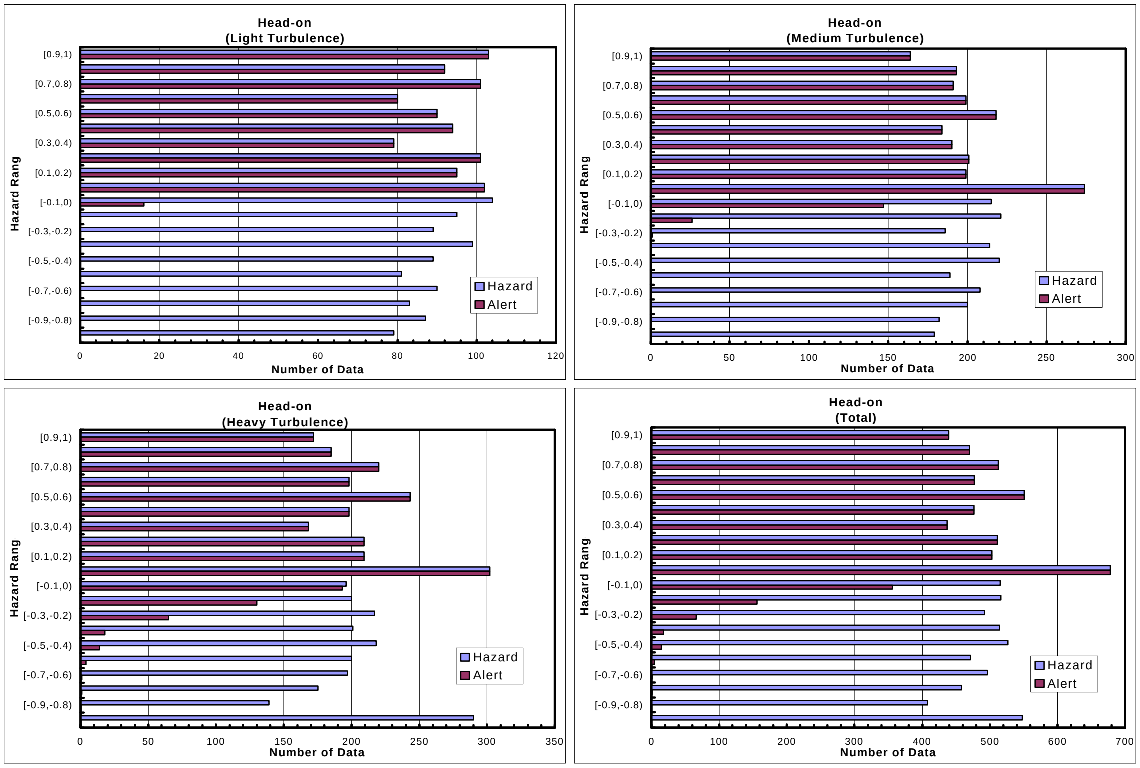


Figure 23: Relative alarm rate for head-on alert testing at various levels of turbulence: light (top left), medium (top right), heavy (bottom left), and combined (bottom right).

Figure 24 and Figure 25 are analogous to Figure 22 and Figure 23, but illustrate scenarios where one aircraft turns across the track of another. The curve/inflection in the hazard vs. time-to-alert curve results from the fact that the opposing aircraft may turn either in front of or behind the subject plane. As with the head-on encounters, the warning time tends to increase with the severity of the conflict and to decrease with increasing turbulence.

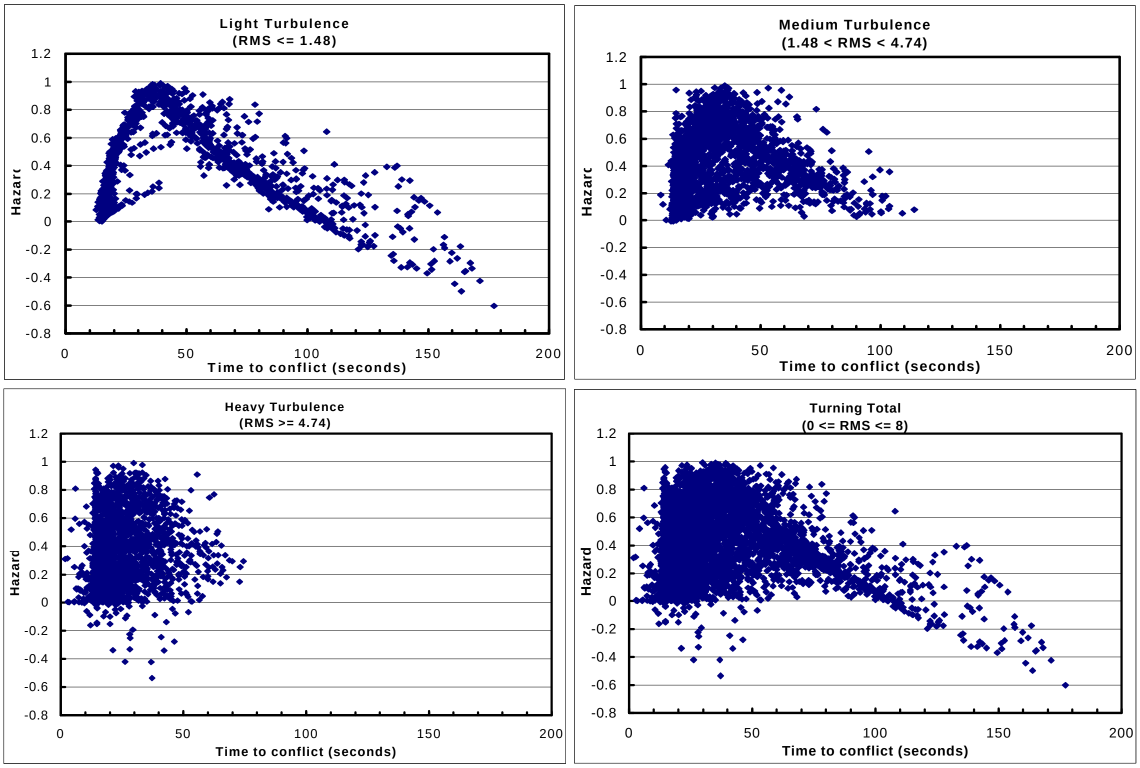


Figure 24: Alert-time vs. hazard (degree of intrusion) for turning conflicts at various levels of turbulence: light (top left), medium (top right), heavy (bottom left), and combined (bottom right).

Note in the plots of hazard vs. nuisance alerts that, here, the higher turbulence runs had *fewer* nuisance alarms. This follows from the fact that in case of higher turbulence (i.e. lower signal to noise ratio) the algorithm often waited longer before declaring an alert. Distant aircraft maintaining a moderate dwell time on the subject aircraft during a slow turn were less likely to cause an alert to be declared.

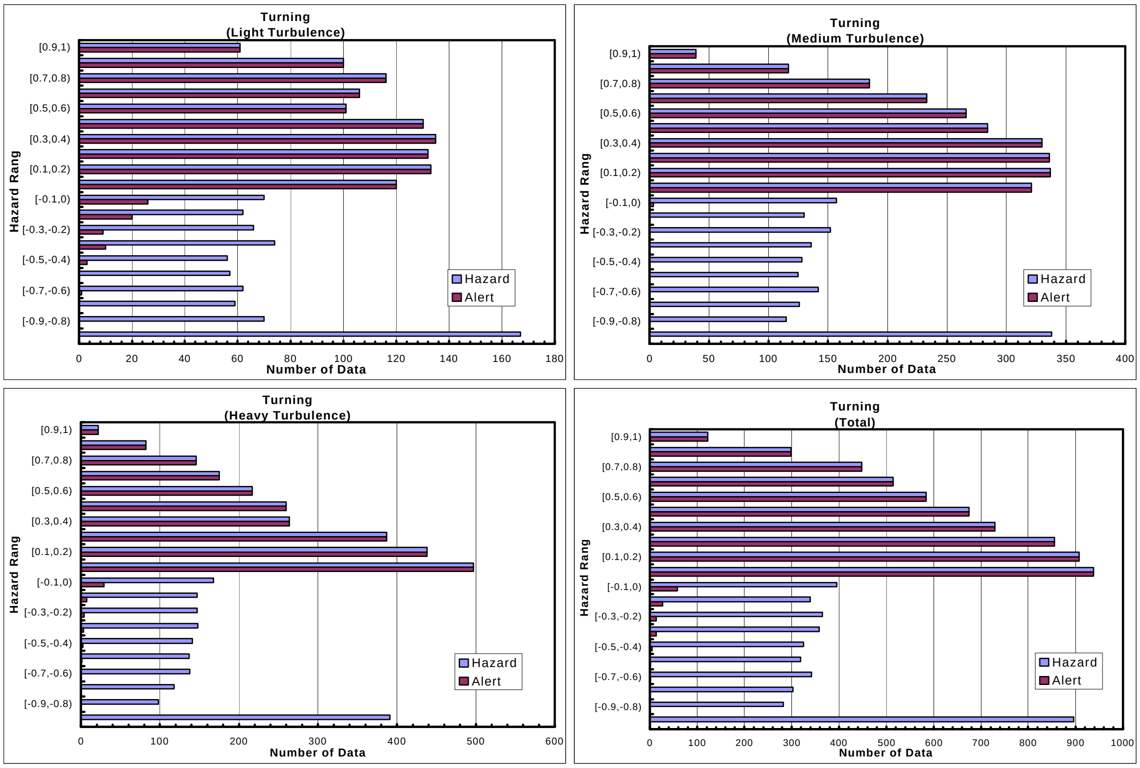


Figure 25: Relative alarm rate for turning conflict alert testing at various levels of turbulence: light (top left), medium (top right), heavy (bottom left), and combined (bottom right).

2.5.5 Position and Velocity Uncertainty Modeling

The simulation model applies both static and dynamic uncertainty to both velocity and position measurements. For both position and velocity in each axis (horizontal and vertical) of each scenario, the Monte Carlo scenario generator operates as follows:

1) A random value for the maximum static error is determined.

2) A random value between 0 and the maximum static error is selected for the actual static error. This static error is applied throughout the simulation.

3) A random value for the maximum dynamic error (wander) is determined. New error values (ranging from 0 to the maximum dynamic error) are generated throughout the simulation run. This during-the-run, random, dynamic error a) has a linear (as opposed to Gaussian) distribution and b) is independent of time; that is, there is no relation between random value **n** and random value **n+1.**

For all but the Close VFR scenario, the values for maximum static and dynamic error used in the simulations are the same. The values are given in Table 9. As described in Table 13 through Table 17, the Assured Normal Separation Distance (ANSD) varies from 1.5 to 5 nautical miles in radius and 500 to 1000 feet in height for the scenarios other than Close VFR. For the Close VFR scenario (Table 18), the ANSD values are 0.2 nautical miles and 300 feet. Because of the very small ANSD values in the Close VFR scenario, the static errors and two of the dynamic errors were set to zero and the maximum dynamic errors for horizontal and vertical positions were set to 0.0165 NM and 50 feet as shown in Table 9. The Close VFR scenario was examined to provide an illustrative and challenging simulation case for close encounters where the position and velocity errors are small.

Scenarios other than Close VFR

	Maximum Static Error	*Maximum Dynamic Error*
Horizontal Position	**1 miles**	**0.1 miles**
Vertical Position	**400 feet**	**30 feet**
Horizontal Velocity	**5 knots**	**2 knots**
Vertical Velocity	**15 fpm**	**10 fpm**

Close VFR Scenario

	Maximum Static Error	*Maximum Dynamic Error*
Horizontal Position	**0 miles**	**0.0165 miles**
Vertical Position	**0 feet**	**50 feet**
Horizontal Velocity	**0 knots**	**0 knots**
Vertical Velocity	**0 fpm**	**0 fpm**

Table 9: Horizontal/Vertical Position/Velocity Error Maximums

2.5.6 Trajectory Uncertainty

Before describing the conflict resolution algorithm, it is useful to examine the three components of the total measured spacing to be maintained between aircraft. These are:

1) Minimum Separation Criteria
The minimum real-world distance to be maintained between the aircraft.

2) Position Uncertainty
The distance that must be added to the measured separation in order to assure that the real-world separation is not less than desired due to position errors.

3) Trajectory Uncertainty
Additional amount of separation required to assure that trajectory uncertainty (due to turbulence, technical flight error, etc.) does not cause the aircraft to stray inside the boundaries of (1) + (2).

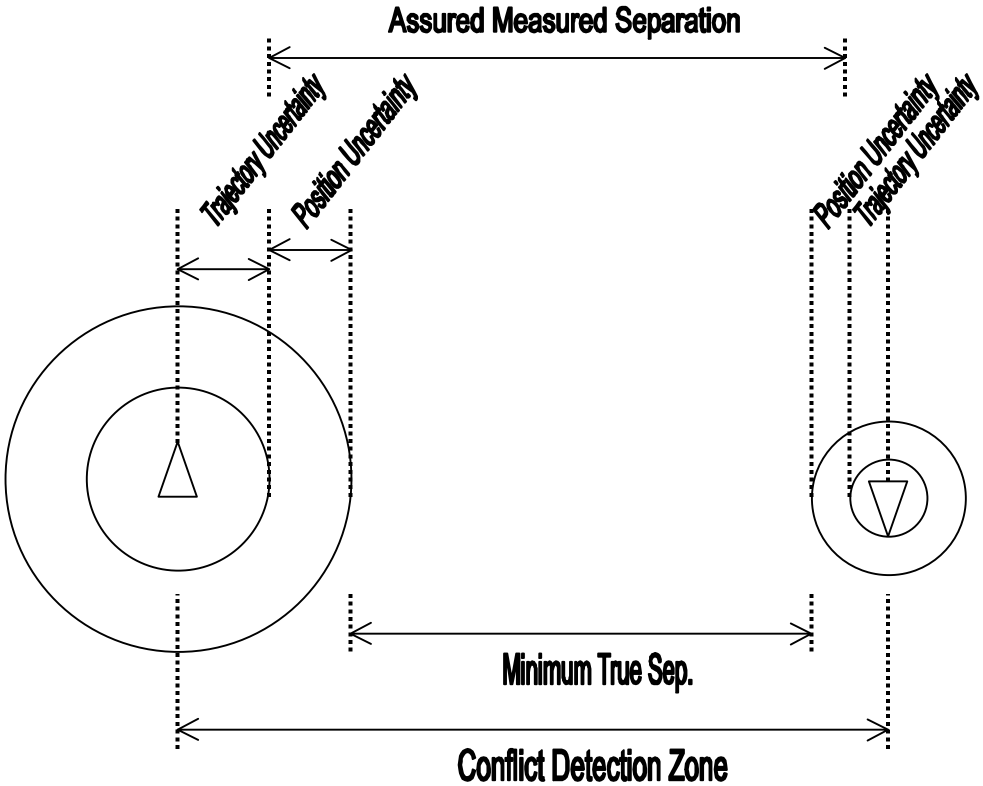


Figure 26: Components of the total measured separation goal.

For the purposes of this work, the trajectory uncertainty was determined by:

1) Flying simulated aircraft "straight and level" on a fixed heading, but with negligible attempt to maintain a particular altitude or ground track for roughly 20 simulated minutes.

2) Repeating (1) for a total of 20 runs, utilizing RMS turbulence values of 0, 2, 4, 6, and 8 knots RMS and airspeeds of 60, 200, 400, and 600 knots.

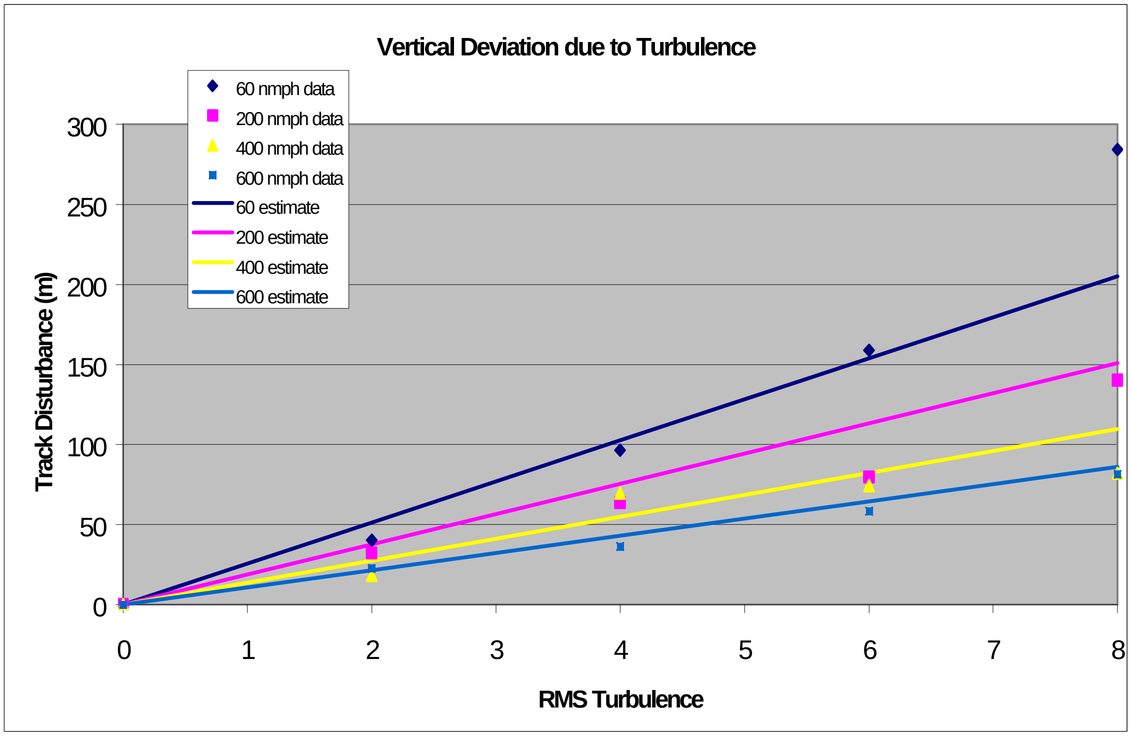
3) Examining the trajectories flown in (2) and extracting the maximum deviation in any 30 second interval.

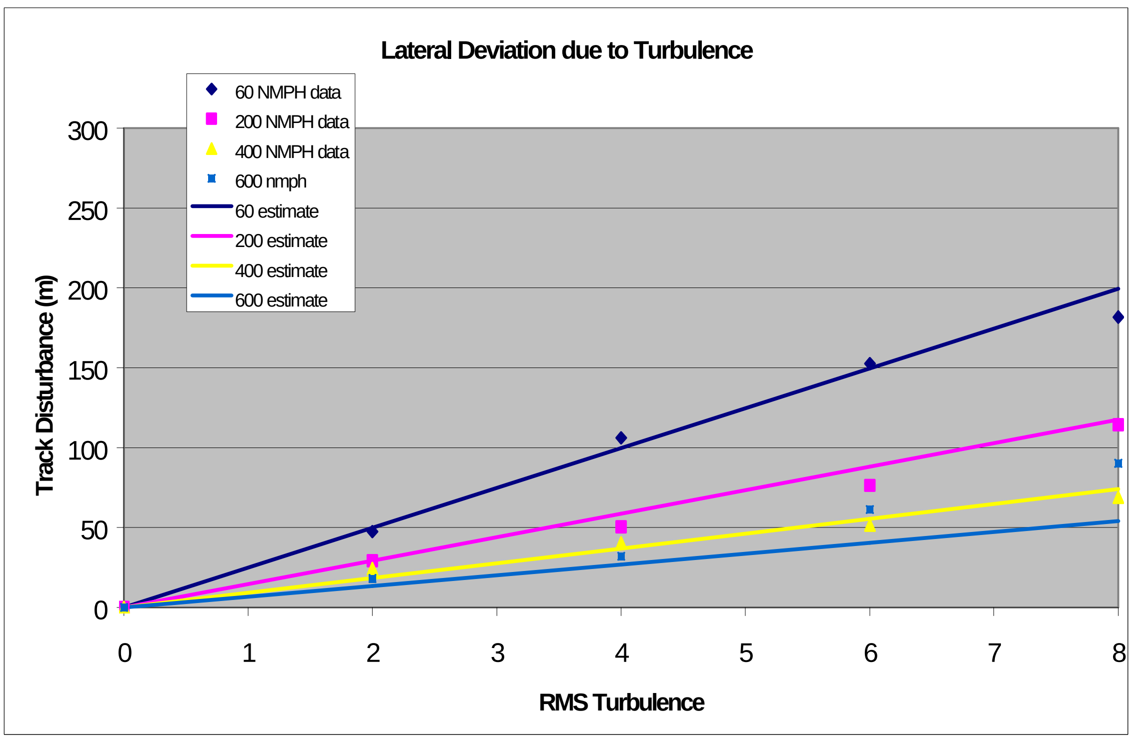
4) Performing a non-linear regression to fit the points to a curve defined by:
   deviation = turbulence / (s0 + s1 * speed)

Having done this, the trajectory uncertainty is estimated as:

Vertical Uncertainty (m) = RMS turbulence / (0.033 + .0001 * speed)

Horizontal Uncertainty (m) = RMS turbulence / (0.028 + .0002 * speed)





2.5.7 Conflict Resolution Algorithm

The list below describes (in slightly simplified terms) what happens (completely independently) on each ACM-equipped aircraft.

a) when a conflict is predicted, the time and positions of the aircraft at the time of closest approach is determined.

b) the point outside the intruder's zone closest to the ownship's position at the time of closest approach is determined.

c) The 3-dimensional distance vector between the projected ownship position and the closest safe point is divided by the time-to-conflict value to produce a resolution vector that, when added to the current velocity vector, acts to reduce/eliminate the conflict.

The process is illustrated in Figure 27 wherein the resolution vector, vz is the sum of the current velocity vector and the maneuver velocity vector, *i*/t. The description above describes a solution involving multiple dimensions, e.g. slowing and turning left. The same principles apply to finding one-dimensional solutions (e.g. bearing change only); the only difference being in the determination of the appropriate 'closest' safe point.

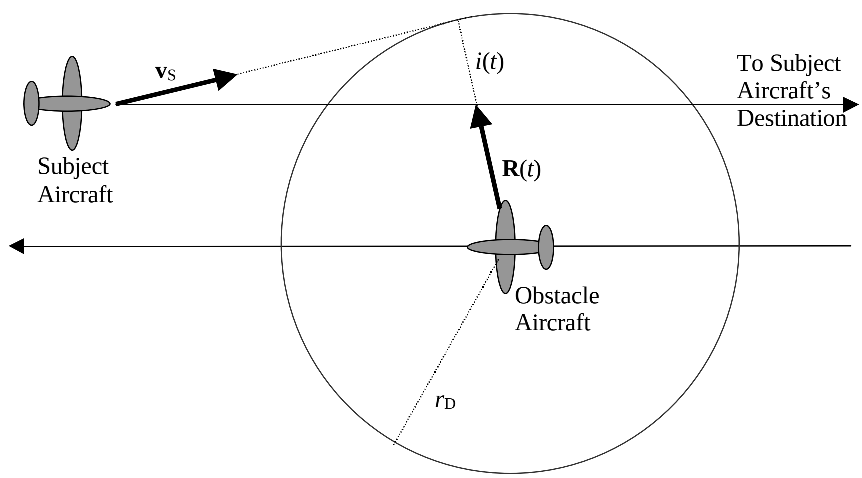


Figure 27: The calculation of conflict resolution maneuvers.

2.5.8 Simulator Structure

The simulator used for these tests is one originally designed to support investigation of Free Flight and self-organizing flight principles and methodologies. In design terms, it is a straightforward implementation of an event-driven simulation system.

Internally, the simulation incorporates one or more aircraft objects, an "airwaves" (radio communications medium) object, and the event "clocker" which manages and orders the actions of the other objects. Each aircraft contains Pilot, NavComputer, Radio, etc. objects necessary to perform the appropriate actions. The initial and goal conditions are specified by a configuration file from which each object reads its own data in turn. Figure 28 is an example of a simulator configuration file.

```
Aircraft=
      ConfigurationOnly=Def
      MinimumSeparation=5.
      NavigationMethod=Direct
```

```
      ResolutionMethod=Cylinder
      Radio=
            TransmitterRange=90.
            TransmitterReliability=1.0
            ReceiverReliability=1.0
            TransmitInterval=3.0/0.2
      Radio Complete
      Constraints=
            SpeedMax=-.10
            SpeedMin=-.10
            AccelMax=.1
            AscendMax=600
            DescendMax=2500
      Constraints Complete
      Navigation=
            PASAS=None
            AlertPASAS=Conservative
            AvoidanceMethod=Bearing
            AlertAvoidanceMethod=Combo
      Navigation Complete
      Pilot=
            PilotInterval=5
            PilotIntervalRandom=1.0
            PilotDelay=0
            PilotAlarmDelay=20
      Pilot Complete
      Turbulence=
            ;1.48 knots = 2.5 ft/s -- light turbulence
            ;2.96 knots = 5 ft/s -- medium turbulence
            ;4.74 knots = 8 ft/s -- heavy turbulence
            RMS=4.
            turbulenceScale=0.288
            simInterval=0.1
            updateInterval=0.25
            LongitudinalFactor=0.1
            LateralFactor=0.2
            VerticalFactor=0.3
      Turbulence Complete
Aircraft Complete

Aircraft=Def
      FlightPath=
            0.0    1.5   3. 3500.
            60.0   0.    3. 3500
            180.0  0.    0.    0.
      FlightPath Complete
Aircraft Complete

Aircraft=Def
      Navigation=
            AlertAvoidanceMethod=Unchanged
            AlertPASAS=Unchanged
      Navigation Complete
      FlightPath=
            0.0    0.    3.    2000.
            80.0   0.    0.    0.
      FlightPath Complete
```

```
Aircraft Complete
```

Figure 28: Abbreviated Example of Simulator Configuration File.

2.5.9 Simulation Parameters and Scenarios

2.5.9.1 Global Test Parameters

All the simulations shared some common parameters:

1) Maximum descent rates of 2500 feet per minute for resolution maneuvers.

2) Maximum climb rates of 600 fpm for resolution maneuvers. It is likely that permitting higher climb rates would have permitted even better separation and/or compensation for turbulence.

3) Maximum horizontal acceleration of 0.1 G and maximum vertical acceleration of 0.1 G for resolution maneuvers. Note: These accelerations apply to the world-frame – not the aircraft's reference frame. For example, the maximum turn is limited to 0.1 G acceleration, implying that the maximum aircraft-normal gravity would be sqrt(1.0 * 1..0 + 0.1 * 0.1) or 1.005 G – very conservative. A longitudinal acceleration of 0.1 G is not so conservative, but speed variations were not part of the test protocol so the acceleration limit does not arise except in the case of sharp turns where the speed of the aircraft decreases in order to execute the quickest turn to the new heading.

4) Maximum range of ADS-B reception was 90 NM (0.0 chance of reception at 90 NM) with a rapidly increasing chance of reception at closer ranges, reaching 0.5 by 70 NM and 0.9 by 40 NM. For practical purposes, the ADS-B range only came into play in the en route scenario.

5) Each scenario was run with three different ACM conditions:

Maneuvering Aircraft	Aircraft 1	Aircraft 2
Aircraft 1	Full ACM system	ADS-B broadcast only – no conflict maneuvering
Aircraft 2	ADS-B broadcast only – no conflict maneuvering	Full ACM system
Both	Full ACM system	Full ACM system

Table 10: Aircraft Maneuvering Scenarios

Aircraft equipped only with ADS-B broadcast capability proceeded as though completely unaware of the conflict. This is the more conservative case since it requires that one aircraft perform the entire deconfliction maneuver, but it does not test the possibility that one aircraft could maneuver in such a way as to defeat the other's deconfliction maneuver.

2.5.9.2 Randomized Test Parameters

The test parameters subject to Monte Carlo randomization were:

1) Turbulence ranged from 0 to 8 RMS knots. To put this range in perspective, light is defined as 1.48, moderate as 2.96, and heavy as 4.74 knots RMS. The implemented turbulence model was 3-D rather than 6-D meaning that turbulence induced translational changes in aircraft position/velocity, but not rotational changes in aircraft attitude or direction of flight. The magnitude of the RMS turbulence was assumed to be uniform in each dimension, but the effect on the aircraft was 3/2/1 for vertical/lateral/longitudinal, respectively.

   The changes in the velocity state vector which the aircraft experienced due to turbulence were directly passed on to the velocity state-vector in the broadcast ADS message, i.e. no smoothing of velocity was implemented.

2) Static position error (offset) bounds ranged up to 1 mile horizontal and 400 feet vertical.

3) Actual static position error ranged up to 100% of the bounding value.

4) Wander in position error ranged up to 0.1 NM horizontal, 30 feet vertical.

5) Total broadcast error bound was the total of (2) and (4).

6) Static velocity error (offset) bounds ranged up to 5 knots horizontal and 15 fpm vertical.

7) Wander in velocity error ranged up to 2 knots horizontal, 10 fpm vertical. (The ACM algorithms did not attempt to bound errors associated with static and dynamic velocity error or compensate for same. These errors resulted in modest errors in the calculation of conflicts and resolutions which became smaller as the time to closest approach neared.

8) ADS-B transmit/reception reliability was fixed at 100%, but a similar effect was achieved by running the trials with average transmit intervals ranging anywhere from 2 to 16 seconds.

9) Two types of pilot delay were modeled:

   Piloting Interval: The interval at which the simulated pilot would give new directions to the aircraft. In conceptual terms we may think of an aircraft being controlled by a pilot who gives all instructions through an autopilot. This parameter is the frequency at which the autopilot is updated. It ranged from 1 to 5 seconds.

   Alarm Delay: This parameter determines how much time passes between the initial annunciation of the conflict detection alert and the time when the pilot begins using the output of the resolution algorithm to fly the aircraft. It ranged from 2 to 20 seconds.

Note that there is no randomization of starting/ending positions. The decision not to randomize the aircraft trajectories was based on several factors. A)

Configuring for maximum conflict is conservative; it requires the maximum maneuvering. B) Because the simulated pilots always attempt to fly the most direct course to their goal (i.e. there is not adherence to a specific ground-track or flight level), turbulence, particularly at higher RMS values, introduces considerable randomization into the conflict configurations.

2.5.9.3 Scenarios

The test scenarios are those described in an earlier version of the Airborne Conflict Management Application Description prepared by the ACM Subgroup of RTCA Special Committee 186, Working Group 1. ~~The scenarios are quoted below, taken from version 2.2 (February 20, 2002) of the ACM Application Description. The subgroup later modified the list of scenarios, deleting one and adding another as shown in Table 11.~~ These original scenario set was revised, ~~S~~and section 1.2.7 contains the current scenarios. Two of these scenarios were not included in the testing. The Misidentification of Conflicting Aircraft (section 1.2.7.4) scenario involved a problem with visual acquisition not applicable to ACM algorithm testing. The Future End State (section 1.2.7.7) scenario was not tested because it describes future end-to-end flight rather than an ACM traffic encounter. One additional scenario was added. The scenarios were chosen to be representative of the common, problematic, real-world flight conflicts which ACM is expected to resolve/mitigate.

The locations of the scenarios are listed in Table 11

Scenario Title	**Short name**	**Description location** ~~**Paragraph from Section 1.2.7**~~
Test Scenario 1 - Conflict on approach with no visual acquisition	High-low	1.2.7.1
Test scenario 2 - Conflict during pattern entry	Pattern	1.2.7.2
Test scenario 3 - Conflict between missed approach and crossing traffic	Abort	1.2.7.3
Test scenario 4 - Conflict with non-transponder equipped aircraft	Tracon	1.2.7.5
Test scenario 5 - High speed, head-on conflict, reduced crew vigilance	Enroute	1.2.7.6
Test scenario 6 - Small PAZ, random conflict configuration	Close	2.5.9.3.1~~Not included in Section 1.2.7~~

Table 12: Test scenario description location~~comparison~~

~~2.5.9.3.1GA Scenario 1. Conflict on approach with no visual acquisition.~~

~~An ACM-equipped King Air making an approach to an uncontrolled municipal airport descends through a scattered cloud layer. An ADS-B-equipped Cessna 172 flying below the clouds is practicing touch and go landings. The King Air pilot is on the radio to the ATC Center canceling IFR when the Cessna turns onto~~

~~final, missing the Cessna's position report on the common traffic advisory frequency. The King Air's ACM notifies the pilot of a low level conflict and the pilot responds by executing a visual go-around and announcing position on CTAF. The Cessna pilot is made aware that the King Air is nearby, but not (any longer) a collision threat. The Cessna continues its approach and lands safely.~~

~~2.5.9.3.2GA Scenario 2. Conflict during pattern entry.~~

~~The pilot of an ADS-B-equipped Mooney Eagle approaches the downwind leg of a busy GA pattern at an uncontrolled airport. In approaching the pattern, the pilot's estimation of the appropriate aim point to merge without creating a conflict is a poor one, and a conflict with an ACM-equipped Cirrus SR22 on the downwind is created. The conflict is a low level one, and the Cirrus pilot waits to see if the conflict is resolved. As the Mooney gets closer, its pilot realizes that the entry requires adjustment and comes right a few degrees, resolving the conflict and ending the low level alert on the Cirrus.~~

~~2.5.9.3.3GA Scenario 3. Conflict between missed approach and crossing traffic.~~

~~A Piper Warrior is making a mid-field crossing at an uncontrolled airport. A Beechcraft Bonanza on final approach chooses to execute a missed approach due to turbulence from thermals near the end of the runway. As the Bonanza's vertical speed changes from a slow descent to a fast climb, the ACM systems on both aircraft produce CDZ-level alerts and provide conflict resolution instructions. Both pilots follow their MAs and separation is maintained.~~

~~2.5.9.3.4Terminal Area Scenario 4. Conflict with non-transponder equipped aircraft.~~

~~UPS 9802, an ACM equipped Boeing 767 en route from SDF to ANC is being vectored by Anchorage Approach control. A Capstone-equipped Cessna 172 with no transponder has just departed Merrill Field VFR. The Cessna inadvertently maneuvers into the path of the 767 that is on a radar vector downwind. The controller is handing off another aircraft to the tower and does not see the Cessna blunder. The 767 Captain receives a CDZ MA to climb out of the path of the Cessna and prevents a collision.~~

~~2.5.9.3.5En route Scenario 5. High Speed, Head on conflict, reduced crew vigilance.~~

~~Near midnight over the Rocky Mountains, United 1492 is headed easterly to Columbus, Ohio and has just departed FL330 in a cruise climb to FL 370. Meanwhile, United 1578 is headed west to Los Angeles from Dulles, level at FL 350. Both cockpits are darkened, quiet, calm, and on autopilot. When still 30 NM from each other, the two ACM equipped aircraft both receive a CDZ MA alert. Still nearly two minutes from a loss of separation, the crew of 1492 notifies ATC of the alert and requests permission to execute a 10 degree right turn, one of the MA choices. The ARTCC controller confirms an impending potential loss of separation and clears 1492 to execute the turn. The planes uneventfully pass with 6 NM separation at FL 350.~~

~~2.5.9.3.6~~2.5.9.3.1 Close VFR Scenario 6. Small PAZ, random conflict configuration. ~~.~~

The Close VFR scenario is not analogous to the other six scenarios. Rather than performing variations on one configuration, it is, instead, a study of an entire range of conflict configurations involving very small protected zones. A random conflict generator was created to produce 10,000 scenarios fitting the following criteria:

1. 50 feet vertical and 90 feet horizontal wander in position report.
2. Horizontal speeds between 80 and 200 NMPH.
3. Vertical speeds between -1600 and +600 fpm.
4. Scenarios wherein the random generator caused the two aircraft to take initial positions in close proximity were filtered out.

The other criteria altered for the Close VFR simulations:

1. No fixed offset error in either position or speed.
2. A protection zone of 300 feet vertical and 0.2 miles horizontal.
3. Maneuvering up to 0.25 Gs.

~~2.5.9.3.7GA Scenario 7. Misidentification of conflicting aircraft~~

- ~~*Not included in the testing – this scenario involved a problem with visual acquisition not applicable to ACM algorithm testing.*~~

2.5.9.4 Scenario-specific Parameters

Scenario #1: high-wing vs. low-wing	
ANSD Height	500 feet.
ANSD Radius	2 NM.
Resolution	Horizontal-only
Description	Higher, faster, low-wing aircraft #1 turns on to final approach already occupied by lower, slower, high-wing aircraft #2.
Notes	The horizontal-only resolution solution is extremely conservative; when the conflict begins, the aircraft have sufficient vertical separation that simply matching descent rates would resolve the conflict. Resolving it through horizontal movement (changes in heading) requires much more dramatic (and lengthy) maneuvers. (Indeed, in the equipage scenario in which only the slower aircraft maneuvers, it is frequently impossible for it to create sufficient lateral spacing before the faster-moving penetrates the vertical separation spacing.)

Table 13: High-wing vs. Low-wing Conflict Parameters

Scenario #2: pattern entry	
ANSD Height	500 feet.
ANSD Radius	1.5 NM.
Resolution	Horizontal-only
Description	Aircraft #1 attempts to descend to and join downwind leg of pattern as aircraft #2, already in the pattern, turns onto downwind leg.
Notes	This scenario is similar to the high-low scenario in that the conflict occurs while the aircraft have sufficient vertical separation such that simply matching vertical rates would solve the conflict, but, conservatively, the conflict is resolved using changes in heading.

Table 14: Pattern Entry Conflict Parameters

Scenario #3: missed approach	
ANSD Height	600 feet.
ANSD Radius	3 NM.
Resolution	Horizontal-only
Description	Light aircraft #2 executing missed approach encounters light aircraft #1 traversing over airport.

Table 15: Missed Approach Conflict Parameters

Scenario #4: TRACON conflict	
ANSD Height	800 feet.
ANSD Radius	3 NM.
Resolution	Altitude-only
Description	Light aircraft #2 climbing from suburban airfield encounters heavy aircraft #1 in slow descent at crossing angle.

Table 16: TRACON Conflict Parameters

Scenario #5: En route conflict	
ANSD Height	1000 feet.
ANSD Radius	5 NM.
Resolution	Altitude-only
Description	Nearly head-on approach at high speed. Aircraft #1 is slightly faster and 200 feet below Aircraft #2.
Notes	This is the only scenario where the 90 NM limit on ADS-B reception comes into play. Even so, all 30,000 conflict scenarios were resolved satisfactorily.

Table 17: En Route Conflict Parameters

Scenario #6: close VFR	
ANSD Height	300 feet.
ANSD Radius	0.2 NM.
Resolution	Combination (horizontal and vertical maneuvers)
Description	Encounters between aircraft pairs with each aircraft traveling on conflicting trajectories with each aircraft randomly assigned speeds between 80 and 200 knots, climb rates between –1600 and 600 fpm, and angle of approach.
Notes	This scenario also employed a maximum maneuvering of 0.25 Gs, no error in velocity, and much smaller errors in position reporting..

Table 18: Close VFR Conflict Parameters

2.5.10 Findings

The results were extremely encouraging. In broad terms, virtually all conflicts that were not subject to extreme turbulence and/or large update/delay intervals were well solved. Turbulence and radio broadcast interval were found to have the strongest influence on the sufficiency of the resolution. Pilot delay in responding to the alarm had less effect. Position/velocity errors had little or no detrimental effect on achieved separation. (Note that the simulation assumes that the position errors were bounded and those bounds were broadcast, i.e. each aircraft knew the maximum absolute error value of their own aircraft and of all others.) This section describes the results first by individual parameter (e.g. ADS-B broadcast interval) and then by individual scenario (e.g. TRACON encounter).

2.5.10.1 Individual Parameter Discussion

In this section, individual parameters are discussed for each of the conflict scenarios described in sections 2.5.9.3 and 2.5.9.4. Simulation results for turbulence, ADS-B broadcast interval, pilot alarm delay, and piloting interval are analyzed by examining the correlation with the severity of the violation of desired separation distances and the frequency at which those violations occur.

The hazard is normalized to the desired separation distance for each scenario. For example, the ANSD for the missed approach scenario of Table 15 is 3 NM. A hazard of 0.0 means that the two aircraft in an encounter came within 3 NM of each other at the point of closest approach. A hazard of 0.05 indicates that the aircraft came within 2.85 NM of each other; that is, the desired separation was violated by 0.05 × 3 NM, or 0.15 NM. Negative hazard numbers indicate that separation was not lost. A hazard level of -0.1 indicates that the two aircraft came no closer than 3.3 NM in this example.

In the parameter analysis below, the frequency of loss of separation is based on hazard levels being 0.05 or worse.

The correlation tables in Sections 2.5.10.1.1 through 2.5.10.1.4 are based on the corresponding scatter charts and bar charts in Figure 29 through Figure 32. To illustrate how the correlation calculated, consider the High/Low scenario data points on the scatter plot at the top of Figure 29. A line is fit through these widely scattered points and the correlation is calculated as 0.291, shown in Table 19. This is an indication of the severity of separation violations as a function of increasing turbulence, in this example.

Next consider a line being fit through the top of each High/Low bar in the lower part of Figure 29. The correlation is calculated and included in Table 19. In this case the frequency of loss of separation data are very linear with increasing turbulence and the correlation is 0.982.

The various parameters and the associated simulation results are discussed below.

2.5.10.1.1 Turbulence

Hazard/Turbulence Correlations						
	High/Low	Pattern	Missed	TRACON	En route	Close
Severity of Violation	0.291	0.073	0.248	0.133	n/a	0.101
Frequency of Loss of Separation	0.982	0.952	0.957	0.862	0.691	0.386

Table 19: Correlation between degree to which separation is lost and turbulence (top line) and frequency of loss of separation and turbulence (bottom line) for cases that hazard exceeded 0.05.

Turbulence was found to have the most dramatic effect on achieved results. Table 19 and the scatter chart and bar chart of Figure 29 reflect data from runs involving two maneuvering aircraft and show all runs for which the airspace intrusion was more than 5 percent of the desired separation. This is a very small fraction of one percent of the total of 60,000 runs. Note that there is always a positive correlation between turbulence and the severity of the separation violation. Note also that (with the exception of the Pattern scenario) there is a strong (sometimes extremely strong) correlation between turbulence and the frequency/likelihood that achieved separation is 95% or less of the desired separation.

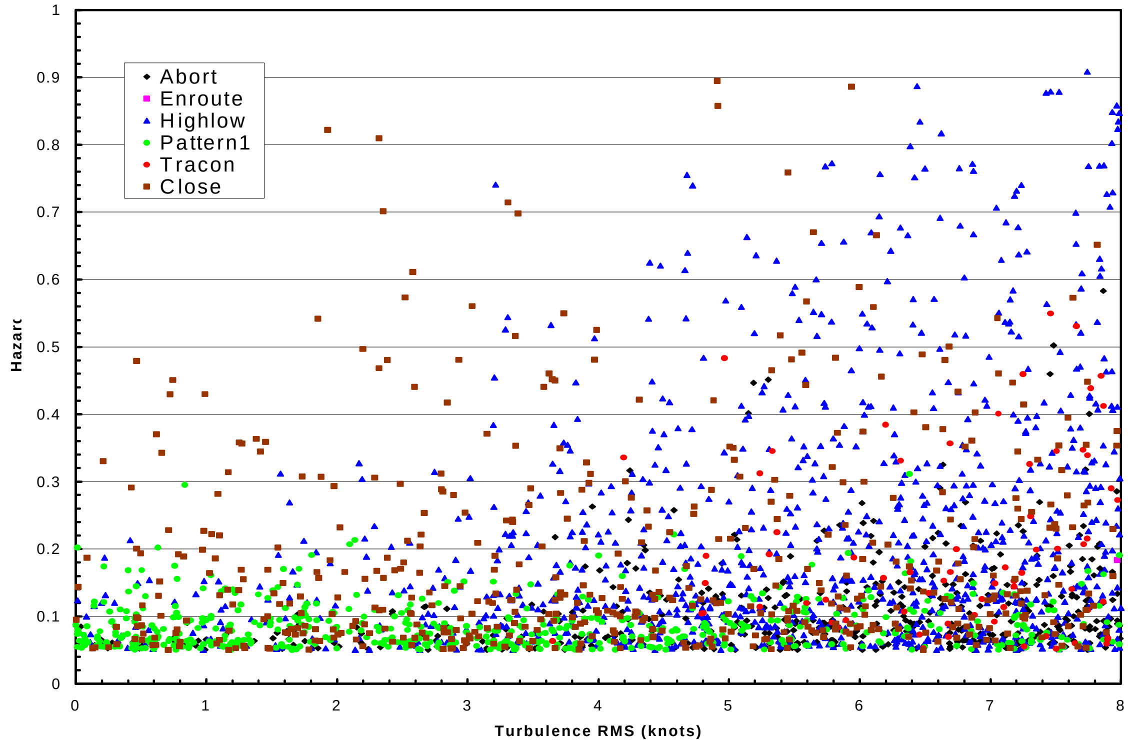
Still, even severe turbulence rarely posed a problem (There were 60,000 runs in all.) except for the High/Low scenario and, to a lesser extent, the Close VFR scenario. The High/Low and Close VFR scenarios are more susceptible to severe turbulence than the other scenarios because:

1) The hazard is measured as a fraction of the desired separation rather than an absolute value. These two scenarios utilize the smallest target separations, hence a violation of any particular absolute distance appears larger in the relative terms utilized in this work.

2) The High/Low scenario utilized conflict resolutions involving changes in heading (resolutions using altitude being much quicker).

3) The High/Low scenarios created conflicts by turns which occurred when the aircraft were already relatively closely spaced so that immediate identification of the conflict was necessary to avoid loss of separation. Note that, on flight decks utilizing full ACM systems, such conflict scenarios would not normally occur. The maneuver initiating the

conflict would be forestalled by the ACM's conflict prevention algorithms (formerly known as "predictive airborne separation assurance system").



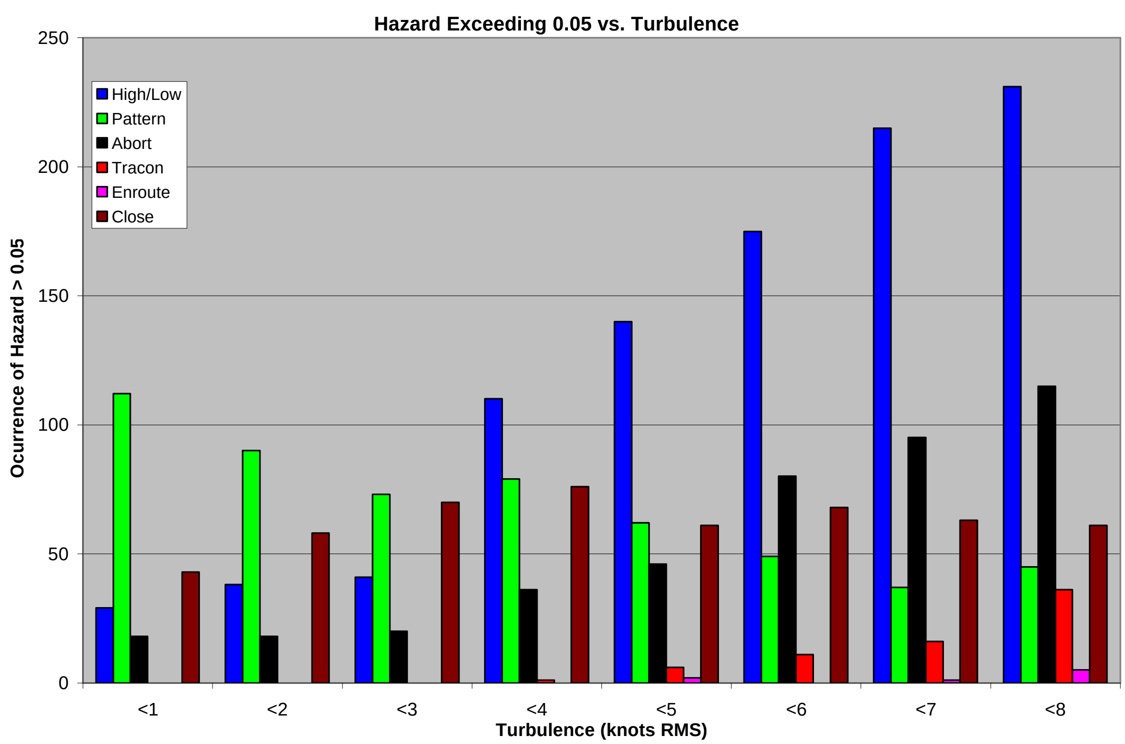


Figure 29: Hazard severity (top) and occurrences (bottom) as a function of turbulence.

The following table presents the data shown in the lower half of Figure 29 in numerical form including the estimated standard error and an assessment of the likelihood that the parameter is significant. Observations:

1) For all cases, there is a moderate to strong correlation between turbulence and the rate at which the desired separation criteria are violated by more than five percent. This is because the range of turbulence investigated extends well into the range where the algorithms (and aircraft structural integrity) begin to degrade.

2) In the Pattern scenario, the occurrence of hazard values greater than 0.5 actually *decreases* with increasing turbulence. The answer lies in the configuration of this particular scenario. The planes begin in close proximity to each other, albeit not on conflicting headings. The turbulence, however, can create momentary headings that are in conflict prior to (or in the earlier stages of) the planned pattern entry maneuver designed to create the conflict

Scenario	Slope	Value	Std Error	Validity Est.
High/Low	Intercept	-7.67261	11.89128	low
	Slope	32.51190	12.60	extremely high
Pattern	Intercept	107.56	5.952287	extremely high
	Slope	-9.79761	1.29123	extremely high
Missed Approach	Intercept	-6.21428	8.475091	low
	Slope	14.92857	1.83850	extremely high
TRACON	Intercept	-8.86904	4.88179	moderate
	Slope	4.40476	1.05901	very high
En route	Intercept	-1	0.98475	moderate
	Slope	0.5	0.21362	high
Close VFR	Intercept	56.30952	6.95360	extremely high
	Slope	1.54761	1.50844	moderate

Table 20: Linear fit of occurrence of hazard > 0.5 to turbulence, occurrence = intercept + slope * turbulence

2.5.10.1.2 ADS-B Broadcast Interval

Hazard/Broadcast Interval Correlations						
	High/Low	Pattern	Missed	TRACON	En route	Close
Severity of Violation	0.293	0.243	-0.123	0.103	n/a	0.213
Frequency of Loss of Separation	0.958	0.966	0.950	0.855.	0.527	0.768

Table 21: Correlation between degree to which separation is lost and ADSB broadcast interval (top line) and frequency of loss of separation and ADS-B broadcast interval (bottom line) for cases that hazard exceeded 0.05.

The effect of increasing radio broadcast interval is not as dramatic as that of increasing turbulence, but it is significant. Note in the chart below that there is a significant increase in hazard severity and frequency as the radio interval climbs above 8 or 10 seconds. Indeed, the top left corner of the chart is relatively devoid of points. The worse-at-greater-intervals effect is most pronounced in the Pattern scenario where there are almost no points on the graph below 8 seconds and a considerable number above 8 seconds. This is the expected result since the aircraft are not even in reception range of each other until approximately 4 minutes before the conflict. The limited time and high velocities increase the importance of frequent reports, particularly when in high turbulence.

Comparing the turbulence plot and the radio interval plot for correlated points reveals that the very highest hazard point recorded had both extremely severe turbulence (roughly 7.8 knots RMS) and relatively high radio broadcast interval (approximately 14 seconds).

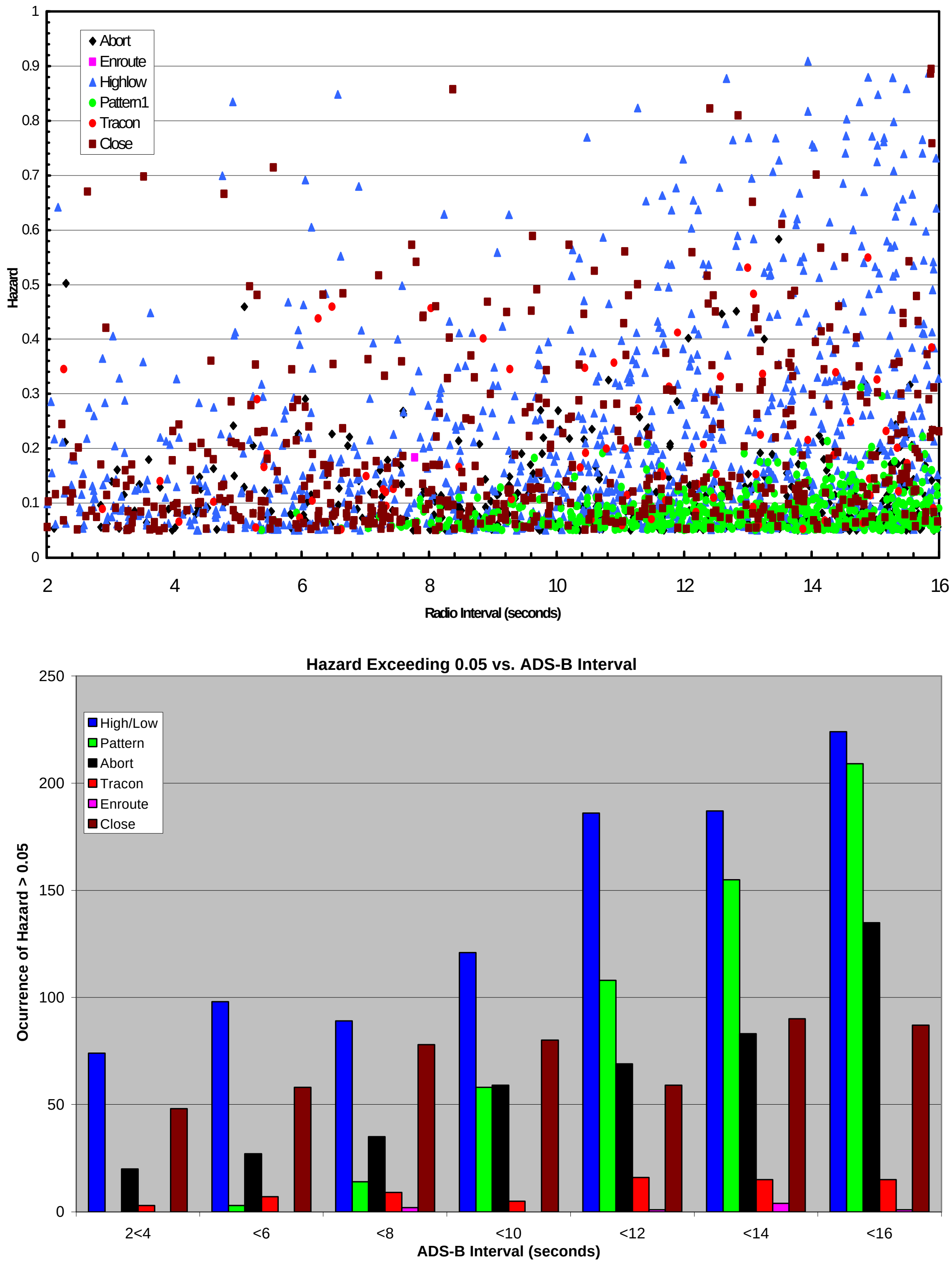


Figure 30: Hazard severity (top) and occurrences (bottom) as a function of ADS-B broadcast interval.

Examining the linear modeling of loss of separation (LOS) occurrence vs. broadcast interval, we find:

1) The validity estimate of the slope (i.e. the probability that occurrence of hazards greater than 0.05 varies with ADS-B broadcast interval) is, on the whole, nearly as high as for turbulence.

2) In all cases, the slope is positive and, most often, by the magnitude of two or three standard error ranges. Clearly, increasing the broadcast interval increases the likelihood of a loss of separation.

3) The intercept value for most scenarios is higher and estimated to be of higher validity – another indication that the ADS-B interval is slightly less a factor than is turbulence.

Scenario	Slope	Value	Std Error	Validity Est.
High/Low	Intercept	23.33928	17.11213	low
	Slope	12.94642	1.737473	extremely high
Pattern	Intercept	-86.5892	21.51561	very high
	Slope	18.30357	2.18457	extremely high
Missed Approach	Intercept	-17.76785	12.6977	low
	Slope	8.76785	1.28925	extremely high
TRACON	Intercept	0.51785	2.81286	very low
	Slope	1.05357	0.28560	very high
En route	Intercept	-0.46428	1.26823	very low
	Slope	0.17857	0.12876	moderate
Close VFR	Intercept	45.39285	10.61431	extremely high
	Slope	2.89285	1.07772	high

Table 22: Linear fit of occurrence of hazard greater than 0.05 to ADS-B interval, occurrence = intercept + slope * interval

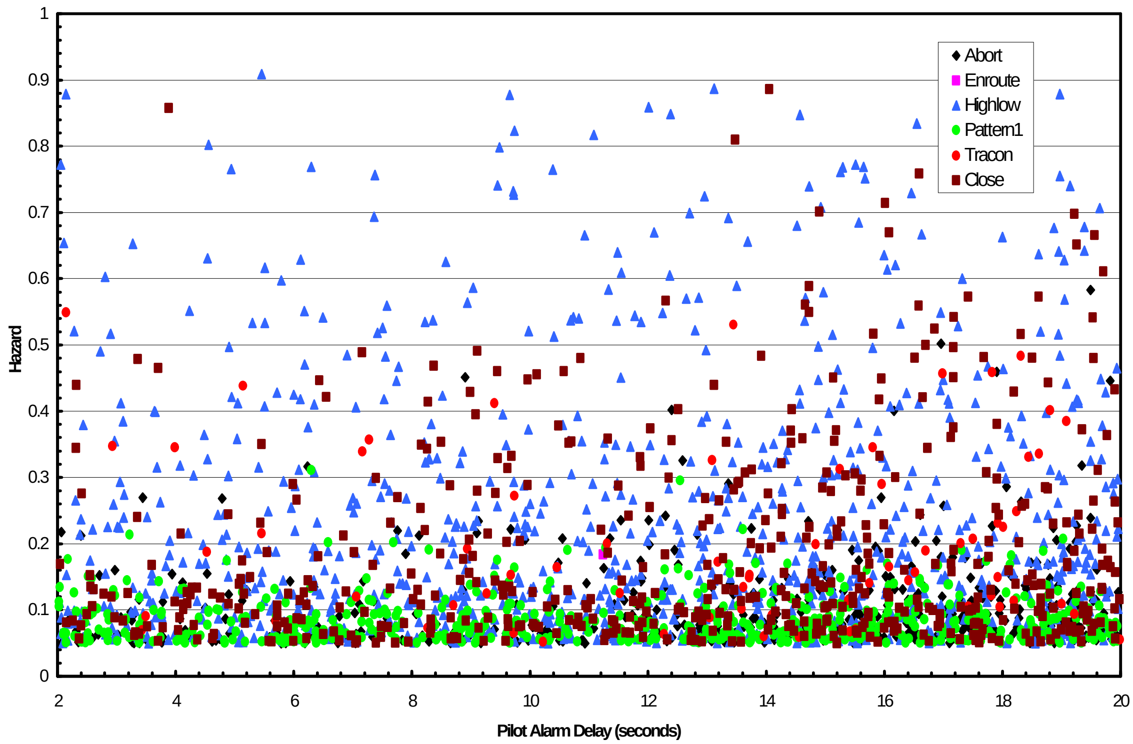
2.5.10.1.3 Pilot Alarm Delay

Hazard/Pilot Alarm Delay Correlations						
	High/Low	Pattern	Missed	TRACON	En route	Close
Severity of Violation	0.050	0.006	0.130	-0.068	n/a	0.14599
Frequency of Loss of Separation	0.938	0.747	0.928	0.853	0.409	0.903

Table 23: Correlation between hazard and Pilot Alarm Delay for cases that hazard exceeded 0.05. Correlation between degree to which separation is lost and delay in responding to conflict alarm (top line) and frequency of loss of separation and delay in responding to conflict alarm (bottom line) for cases that hazard exceeded 0.05.

The pilot alarm delay interval is the length of time after a conflict alert is issued that the pilot tends to other duties (including piloting the aircraft on its current/original trajectory) before acting on any ACM directives. As the plot below shows, failures to well-solve the conflicts become more common as the alarm delay value grows. This is to be expected as the longer the delay in responding, the greater the probability that the maneuver cannot be executed in time to completely resolve the conflict.

While there is a positive slope to the plot of occurrence vs. pilot alarm delay, it is not so pronounced as with hazard occurrence vs. ADS-B interval. This indicates that (over the range of values tested) the rate at which the pilot responds to a conflict alert is not as important for maintaining separation as the broadcast/receive interval.



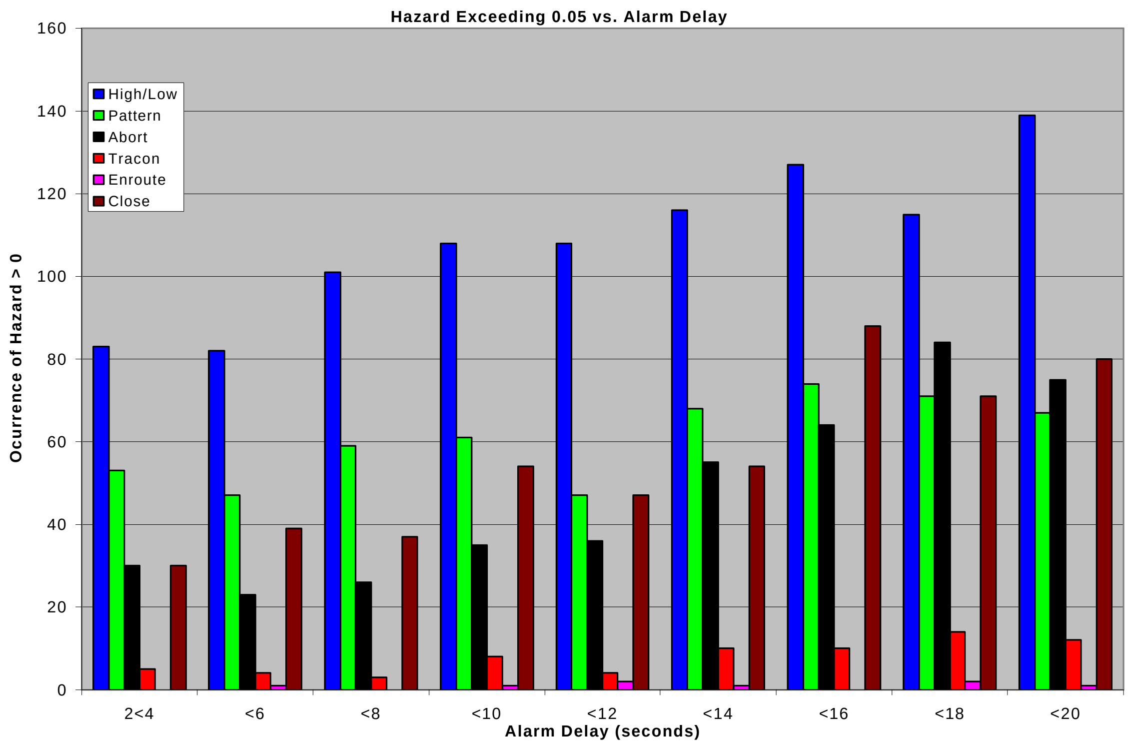


Figure 31: Hazard severity (top) and occurrences (bottom) as a function of piloting alarm delay.

Scenario	Slope	Value	Std Error	Validity Est.
High/Low	Intercept	73.66944	5.42425	extremely high
	Slope	3.19166	0.44637	extremely high
Pattern	Intercept	45.65277	5.62367	extremely high
	Slope	1.37499	0.46278	very high
Missed Approach	Intercept	5.48055	7.03382	low
	Slope	3.82500	0.57882	extremely high
TRACON	Intercept	0.99444	1.73605	very low
	Slope	0.61666	0.14286	very high
En route	Intercept	0.24722	0.59827	very low
	Slope	0.05833	0.04923	low
Close VFR	Intercept	19.07222	7.25092	high
	Slope	3.31666	0.59669	very high

Table 24: Linear fit of occurrence of hazard greater than 0.5 to pilot alarm response delay, occurrence = intercept + slope * delay

2.5.10.1.4 Piloting Interval

Hazard/Piloting Interval Correlations						
	High/Low	Pattern	Missed	TRACON	En route	Close
Severity of Violation	-0.051	-0.015	-0.105	-0.047	n/a	0.004
Frequency of Loss of Separation	0.508	0.934	0.772	0.804	0.683	0.428

Table 25: Correlation between degree to which separation is lost and piloting interval (top line) and frequency of loss of separation and piloting interval (bottom line) for cases that hazard exceeded 0.05.

Conceptually, the pilot interval is the length of time the pilot tends to other duties between updating the aircraft's flight vector. It is a measure of the pilot's attentiveness to actually flying the aircraft. As the plot below shows, the pilot interval does not meaningfully influence the degree of conflict resolution obtained over the range of tested values (1 to 5 seconds). (It is likely, however, that higher values of pilot interval would have degraded the conflict resolution in a manner analogous to that of larger ADS-B broadcast intervals since repeatedly following old instructions is little different than infrequently following frequently updated instructions.

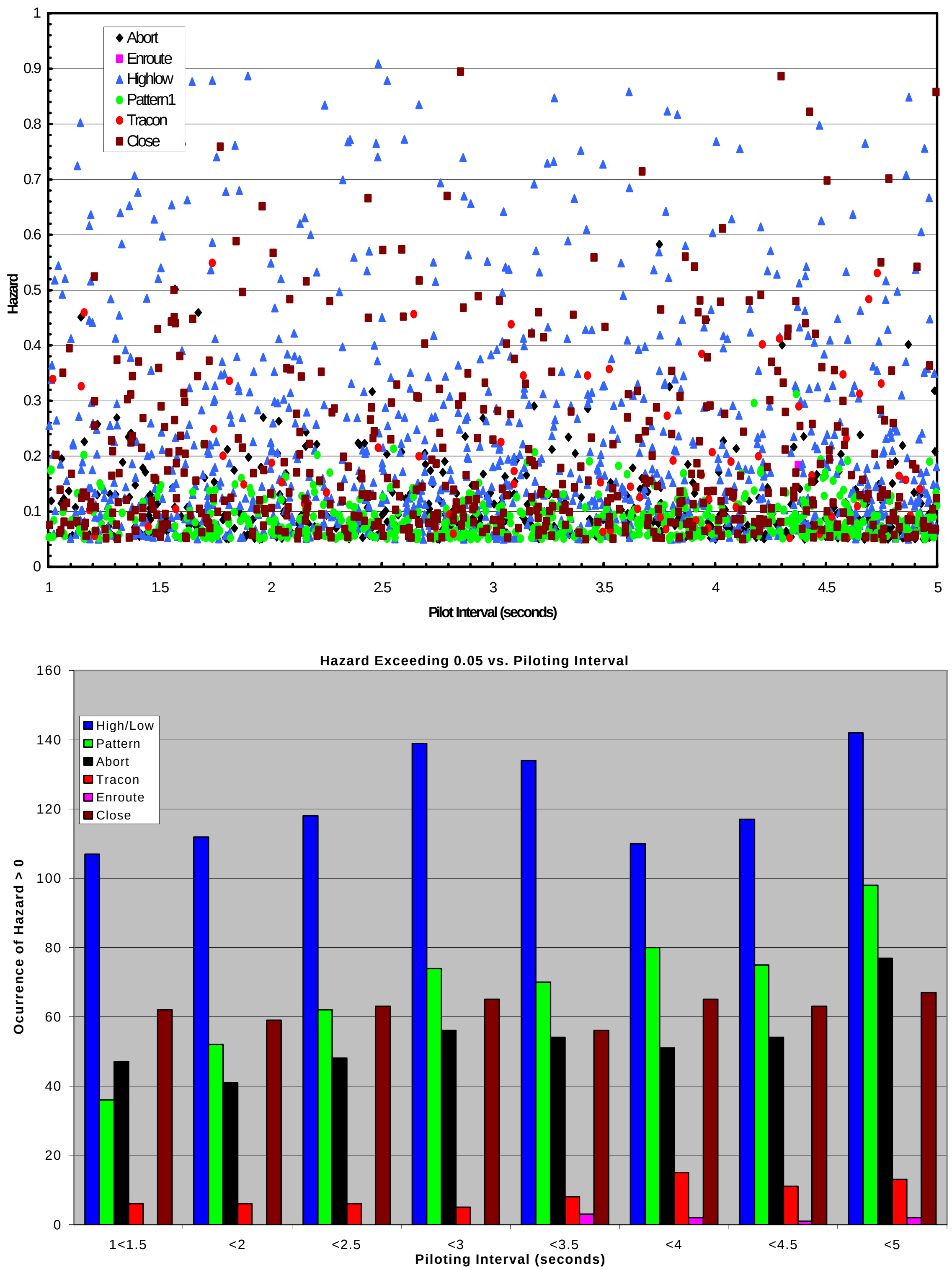


Figure 32: Hazard severity (top) and occurrences (bottom) as a function of piloting interval.

Here, the slope of the individual data series in the occurrence/interval bar chart is nearing zero while the intercept is relatively high.

1) The implication is that frequency of LOS greater than 5% is not sensitive to the piloting update interval. Note however, that the piloting interval was only investigated over a range of 1 to 5 seconds while the other time parameters (ADSB interval and alarm delay) were checked to much higher values. Hence, we have shown that the solution is relatively insensitive to piloting interval in the range of 1 to 5 seconds; we may expect that the resolution does become more sensitive to piloting interval at larger intervals.

2) In terms of the actual maneuvers performed, there is little difference between a small piloting interval combined with a large ADS-B update interval and a large piloting interval combined with a small ADS-B update interval. The result is similar because, in each case, changes in trajectory designed to resolve conflicts can occur only at the rate of the slowest updates.

Scenario	Slope	Value	Std Error	Validity Est.
High/Low	Intercept	105.1607	12.76954	extremely high
	Slope	5.73809	3.97642	low
Pattern	Intercept	25.58928	7.1482	very high
	Slope	14.26190	2.22594	extremely high
Missed Approach	Intercept	33.35714	7.24473	extremely high
	Slope	6.71428	2.25600	high
TRACON	Intercept	1.32142	2.39763	very low
	Slope	2.47619	0.74662	high
En route	Intercept	-1	0.93435	low
	Slope	0.66667	0.29025	moderate
Close VFR	Intercept	58.78571	3.43076	extremely high
	Slope	1.23809	1.06833	low

Table 26: Linear fit of occurrence of hazard greater than 0.05 to piloting interval, occurrence = intercept + slope * piloting interval

2.5.10.1.5 Position Error

Position error had little effect on the success of the conflict resolutions since the magnitude of the maximum error is included in the calculation of desired separation. Indeed, the larger the maximum error bound the lower the hazard (the greater the achieved separation) tended to be since size of the protected airspace was always increased by the maximum error, but the actual error was always less than or equal to that value. For hazard values greater than 0.05, the correlation between hazard and maximum position offset bounds, for example, was on the order of –0.05.

2.5.10.1.6 Velocity Error

Like position error, velocity error also had little effect on the success of the conflict resolutions, but for an entirely different reason. The effect of velocity on resolution maneuvers is a function of the time; the total error is the velocity error multiplied by the time to conflict. As the time to closest approach nears zero, the resolution errors attributable to velocity error also approach zero.

2.5.10.2 Individual Scenario Discussion

This section discusses the six individual scenarios. Each scenario is given its own section and each section contains three items:

1) First, a table displaying a regression analysis fit of the equation:

   Hazard = a * turbulence + b * RadioInterval
   + c*PilotInterval + d*AlarmDelay

   Comparing values between parameters is difficult because each refers to a different physical variable scaled over a different range, but the data can be useful in understanding the factors affecting the success of the resolutions. Also, note that the values are not a fit for all the data points, it is only a fit for those cases that the hazard (the fraction by which the desired separation was penetrated) exceeded 0.05.

2) A summary/discussion of the results of the conflict scenario simulations.

3) Pie charts dividing the runs into a) successful resolutions (those with less than 10% LOS), b) resolutions that were unsuccessful because one or more parameters were "unreasonable", and c) "Other", i.e. resolutions that were unsuccessful even though the parameter values were reasonable. The definition of "reasonable" for the purposes of these attributions are provided in the table below and are applied in the order listed; if a particular simulation case has a turbulence level of 6.2 and a pilot alarm delay of 16 seconds, it will be categorized as "unreasonably" turbulent:

Turbulence	Below "heavy" (4.74 knots, RMS)
ADSB interval	Below 5 seconds
Pilot Alarm Delay	Below 10 seconds

In examining each scenario's charts, note that, for most nearly every scenario, not only are virtually all of the cases with "reasonable" scenarios solved, *most of the cases with one or more "unreasonable" parameters are also solved.*

The last items (if present) in each section are tables describing the parameters utilized and the hazard recorded for each case that the achieved hazard level exceeded 0.10.

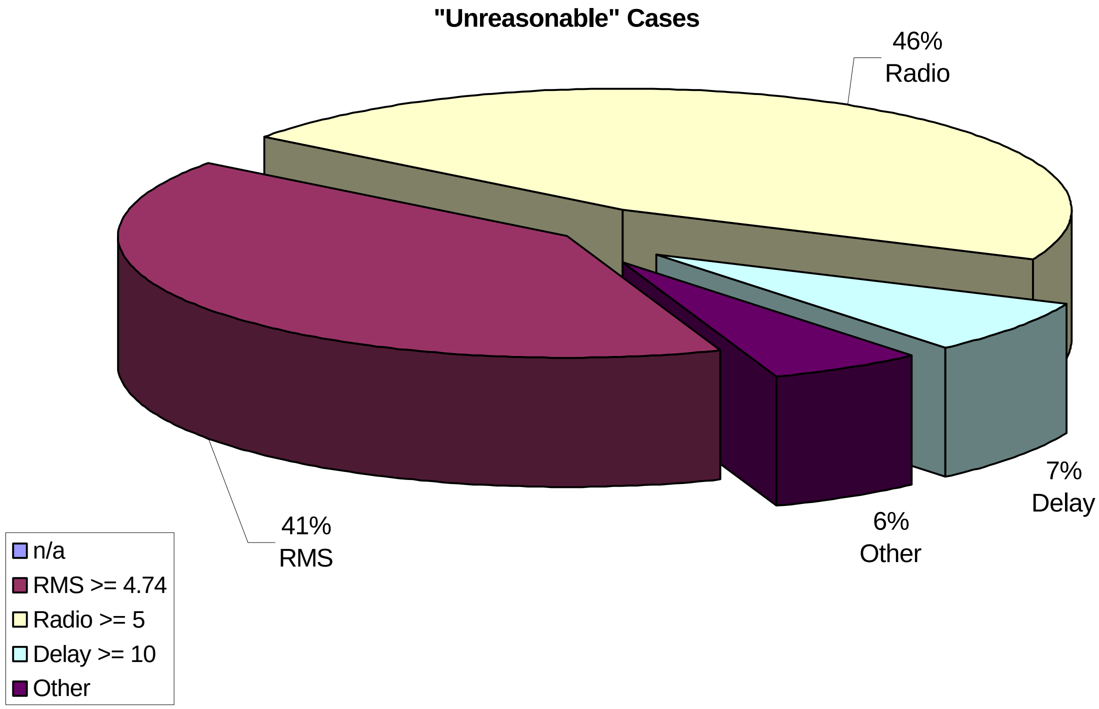


Figure 33: The attribution of failures to be expected if every conflict failed to maintain at least 90% of desired separation.

2.5.10.2.1 High/Low Scenario

Parameter	Estimate	90% low	90% high	std error	Validity est.
Turbulence	0.02775	0.02303	0.03247	0.00286	extreme
Radio Interval	0.01399	0.01167	0.01630	0.00140	extreme
Pilot Interval	-0.03416	-0.0477	-0.0206	0.00822	extreme
Alarm Delay	0.00280	0.00105	0.00454	0.00106	high

Table 27: Regression Analysis to determine parameters fitting
hazard = a * turb + b * radio_interval + c* pilot_interval + d * alarm_delay
to High/Low scenarios in which the loss of separation exceed 5% of the desired separation.

The high wing vs. low wing scenario was the most challenging of any of the scenarios. It involves a high-wing aircraft turning onto final and beginning a descent when a slower, high wing, aircraft is already on final. The conflict occurs when the aircraft are already in close proximity to each other. Observations:

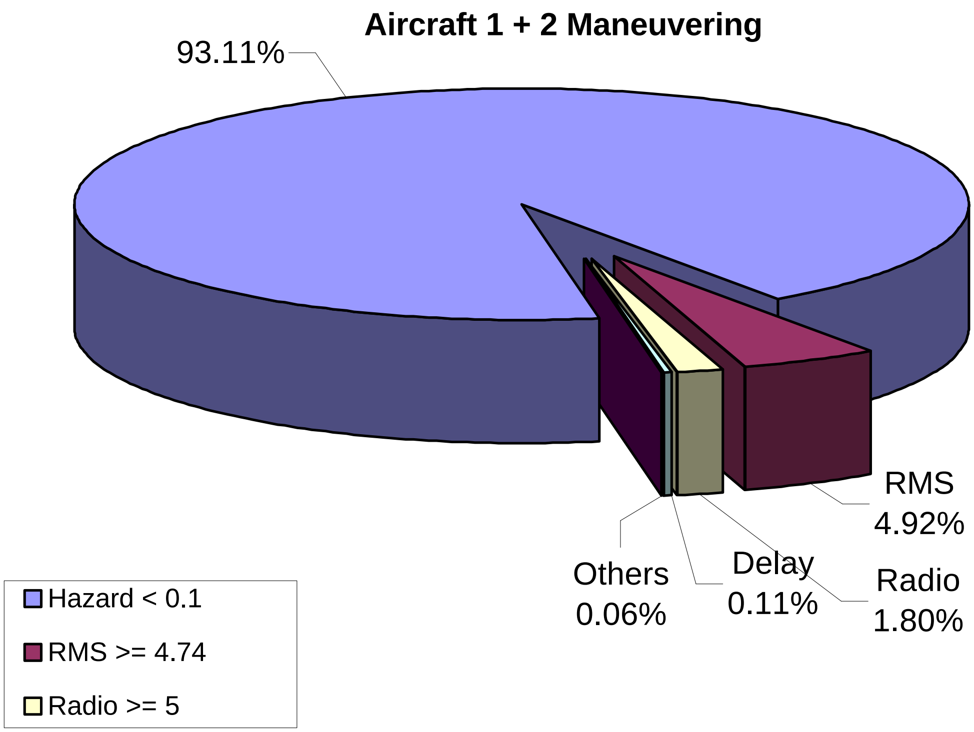
1) If the low wing aircraft were equipped with a Conflict Prevention (CP) system, the conflict would not occur in the first place, as the pilot would know in advance that the maneuver would create a conflict.

2) The conflict time available to resolve the conflict is so limited that when only the slower aircraft is allowed to maneuver ("Aircraft 2

Maneuvering" in the figure below) it fails to keep the hazard below 0.1 58% of the time for all cases and 46% of the time[4] when considering only the cases with "reasonable" parameter values.

3) The reason the time to solve the conflict is so small is two-fold. First, the scenario uses a horizontal resolution (aircraft must move 2 miles) vs. a vertical resolution (aircraft must move 1/20th that distance). Secondly, the horizontal protection radius of 2 miles is quite large.

4) Despite the difficulties presented by this scenario, the results – at least for the two sub-scenarios that provide sufficient time to resolve the conflict are quite good. Ninety-two or 93% of all conflicts are resolved to a hazard of 0.1 or less with 99% of the "reasonable" cases being so resolved. Of the reasonable parameter cases not resolved, none exceeded 0.35 and only two exceeded 0.2.



[4] Unlike the rest of the scenarios in this section, there is not, for this scenario, a break-out of parameters for the 260 "reasonable" cases that experienced a hazard ratio greater than 0.1.

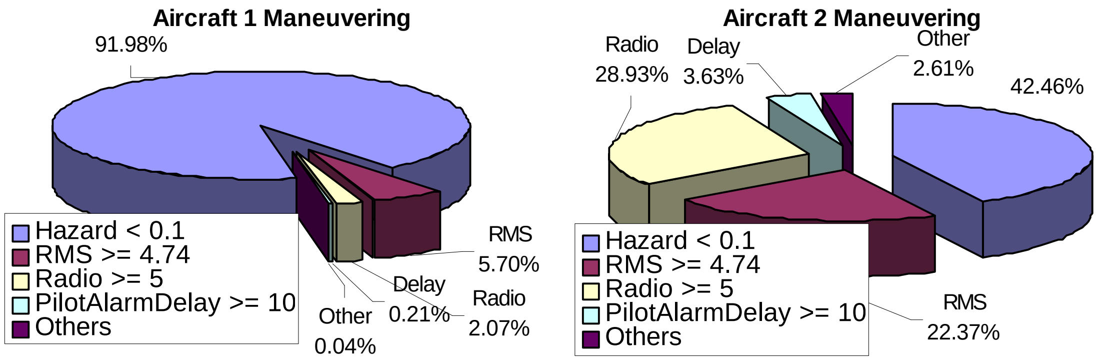


Figure 34: High/Low Resolution Attribution

Radio Interval	Pilot Interval	Pilot Alarm Delay	Turb RMS	AlertTime	Hazard
3.8673	1.2676	6.101	4.704	53.17351	0.110624
4.0409	3.3045	6.3781	3.1458	32.35761	0.129471
2.8871	2.9299	5.3436	3.2492	45.16955	0.132971
3.8941	4.2135	3.5886	1.4074	50.05114	0.144552
4.0397	4.6283	8.2799	2.1688	33.72859	0.327288
3.5155	4.9562	5.045	3.7349	56.15571	0.358233

Table 28: Cases of “Aircraft 1 & 2 Maneuvering” for which Hazard exceeds 0.1

Radio Interval	Pilot Interval	Pilot Alarm Delay	Turb RMS	AlertTime	Hazard
2.1236	4.4513	6.9961	3.6978	170.6629	0.103958
4.6879	1.7913	4.4648	3.651	43.22554	0.105163
2.1988	2.5056	8.249	0.6563	45.63086	0.108743
3.5155	4.9562	5.045	3.7349	56.15571	0.154788

Table 29: Cases of “Aircraft 1 Maneuvering” for which Hazard exceeds 0.1

2.5.10.2.2 Pattern Entry Scenario

Parameter	Estimate	90% low	90% high	std error	Applicable
Turbulence	0.00098	0.00009	0.00206	0.00065	doubtful
Radio Interval	0.00366	0.00262	0.00470	0.00063	extreme
Pilot Interval	0.01078	0.00597	0.01559	0.00291	extreme
Alarm Delay	0.00013	-0.00033	0.00059	0.00028	poor

Table 30: Regression Analysis to determine parameters fitting hazard = a * turb + b * radio_interval + c* pilot_interval + d * alarm_delay to Pattern Entry scenarios in which the loss of separation exceed 5% of the desired separation.

The conflict configuration of this scenario is not greatly different than the high/low scenario, but the results are excellent (every “reasonable” case and 99% of all cases solved to 0.1 or better for all three equipage scenarios) even though the protected airspace zone was 25% smaller in diameter (1.5 nautical miles). This is because the aircraft were not in such close proximity when the conflict occurred and was detected, and because the configuration of the conflict was such that the closing rate was relatively low.

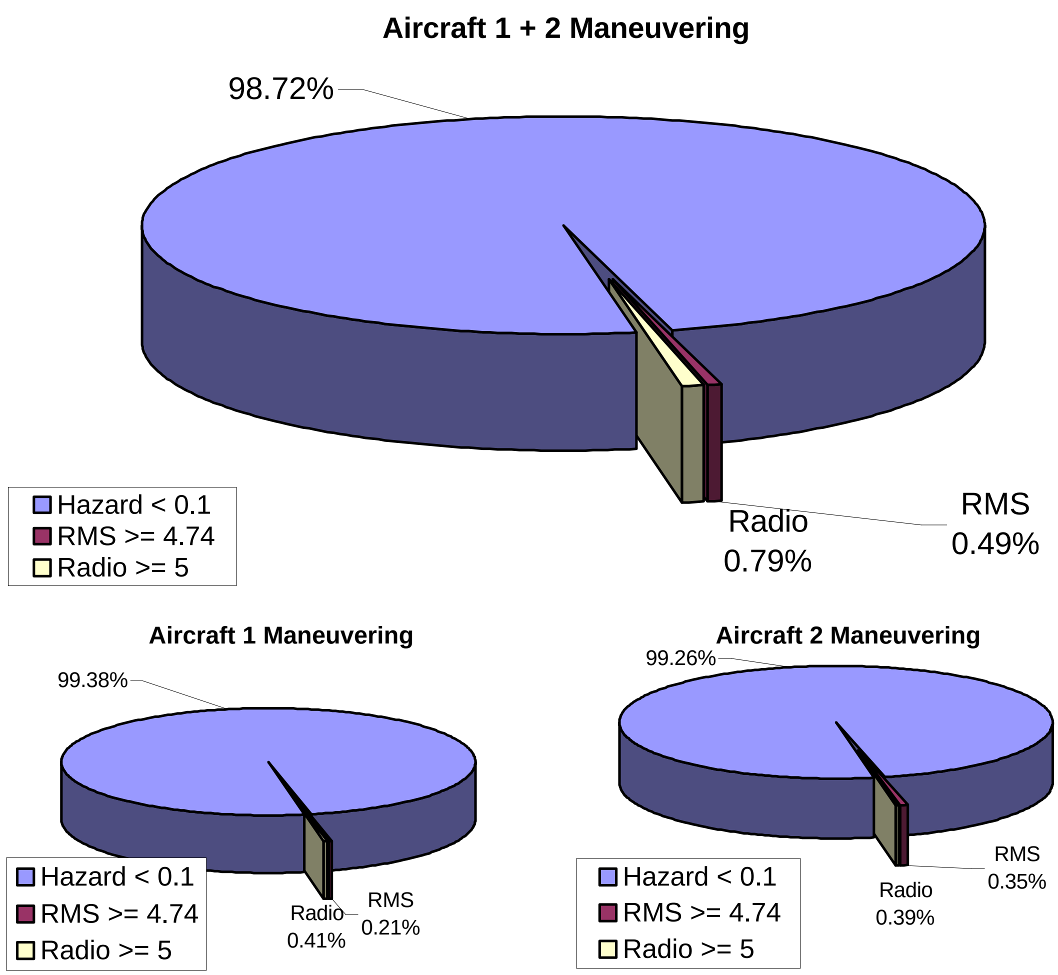


Figure 35: Pattern Entry Resolution Attribution

2.5.10.2.3 Missed Approach Scenario

Parameter	Estimate	90% low	90% high	std error	Applicable
Turbulence	0.00794	0.00504	0.01084	0.00176	extreme
Radio Interval	-0.00105	-0.0026	0.00053	0.00095	doubtful
Pilot Interval	0.01942	-0.04149	0.02929	0.00598	extreme
Alarm Delay	0.00120	0.00006	0.00233	0.00068	high

Table 31: Regression Analysis to determine parameters fitting hazard = a * turb + b * radio_interval + c* pilot_interval + d * alarm_delay to Missed Approach scenarios in which the loss of separation exceed 5% of the desired separation.

The missed approach scenario was another of the more difficult conflict configurations. The conflict is created when an aircraft descending to touchdown at an airport aborts the approach and begins climbing into the path of an aircraft that is traversing the airport at altitude. The conflict is created 3 minutes out in time, 4.5 miles out for the aircraft climbing with an airspeed of 90 knots and 12 miles out for the traversing aircraft cruising at 180 knots. Observations:

1) When both aircraft are permitted to maneuver, 98% of all the cases and all of the "reasonable" cases are well solved.

2) When only one aircraft is permitted to maneuver, the resolution was still very good when the faster aircraft was allowed to maneuver, but less good when the slower, climbing aircraft was required to maneuver. (In none of the "reasonable" cases, however, did the hazard ratio exceed 0.3333. That is, more than 2 nautical miles / 400 feet of the desired 3 nautical miles / 600 feet was always maintained.

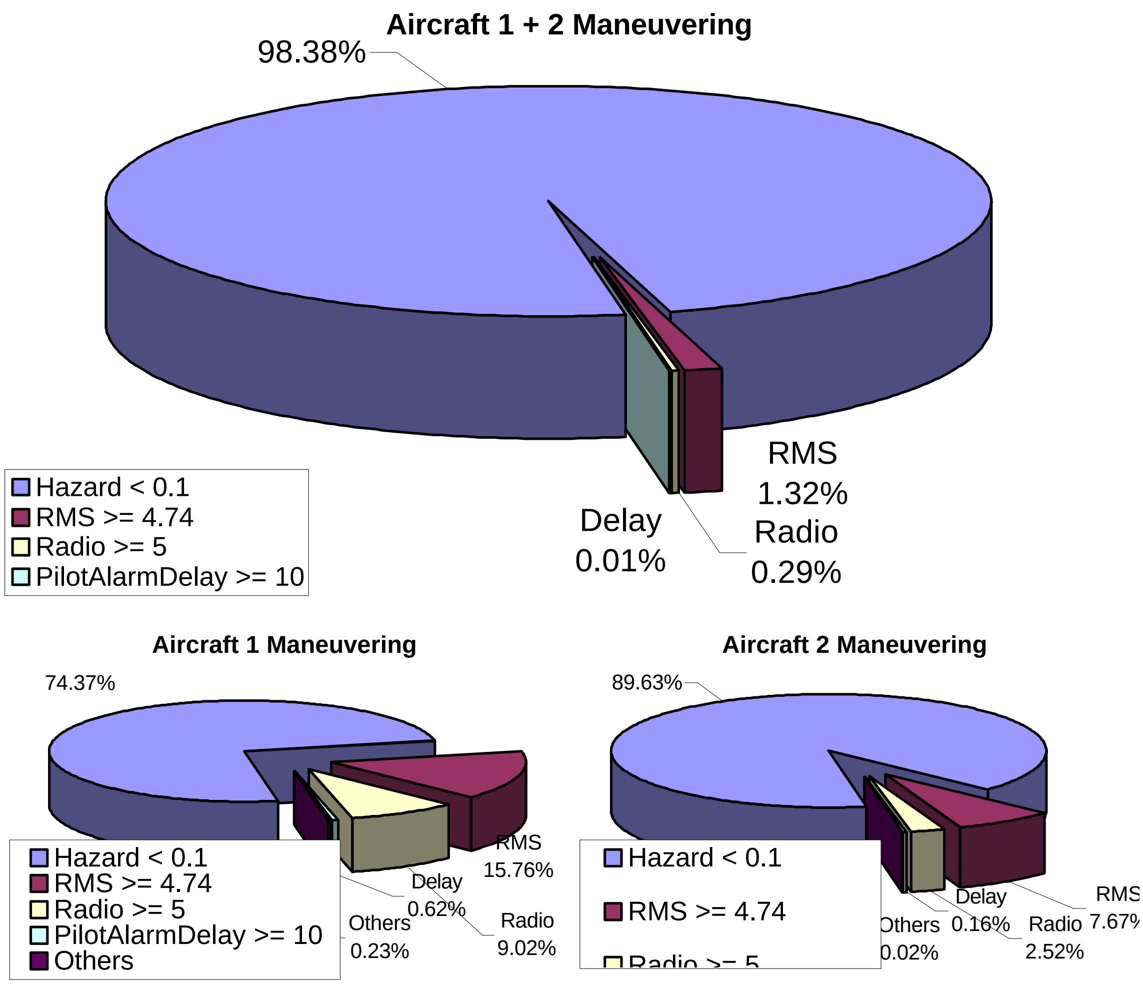


Figure 36: Missed Approach Resolution Attribution

Radio Interval	Pilot Interval	Pilot Alarm Delay	Turb RMS	Alert Time	Hazard
3.5155	4.9562	5.045	3.7349	62.07448	0.102567
2.4183	2.1788	8.8527	4.2421	41.53631	0.10425
2.7591	1.7888	5.522	4.7106	59.77514	0.109995
4.3132	1.9354	3.2702	4.0403	41.71379	0.117016
2.9385	1.3615	2.5092	3.3016	44.81385	0.118514
4.4346	4.4698	6.5088	4.6398	32.34295	0.118664
3.8676	4.4274	5.6921	4.4318	40.12983	0.125973
3.988	3.5693	6.322	3.0022	59.05092	0.126377
2.8542	4.706	8.4542	3.9215	67.33103	0.135006
4.8978	4.308	2.9916	3.089	78.34105	0.14239
2.5278	4.108	4.476	4.3401	43.3259	0.153691
4.5685	2.4659	3.2113	3.1905	74.55608	0.157
2.3241	2.9916	8.2891	4.3842	72.60588	0.158508
4.7505	3.3085	7.4865	3.322	61.91002	0.171213
3.8673	1.2676	6.101	4.704	51.62218	0.171305
3.1507	2.0221	4.0371	4.1664	39.48786	0.182541
3.8777	2.6003	2.2625	3.3961	55.2474	0.185897
4.9961	3.2848	3.0858	4.5138	43.20385	0.187455
4.8208	1.8522	8.3007	4.6717	48.22978	0.227038
4.6879	1.7913	4.4648	3.651	49.0345	0.229323
2.1138	4.0068	4.6837	4.723	53.05247	0.243337
2.8241	2.1802	3.0926	4.7201	40.03939	0.247027
4.7048	1.3441	6.827	4.4355	73.67761	0.314488

Table 32: Cases of "Aircraft 1 Maneuvering" for which Hazard exceeds 0.1

Radio Interval	Pilot Interval	Pilot Alarm Delay	Turb RMS	Alert Time	Hazard
4.6879	1.7913	4.4648	3.651	49.0345	0.126255
3.1507	2.0221	4.0371	4.1664	39.48786	0.193642

Table 33: Cases of "Aircraft 2 Maneuvering" for which Hazard exceeds 0.1

2.5.10.2.4 TRACON Scenario

Parameter	Estimate	90% low	90% high	std error	Applicable
Turbulence	0.01611	-0.00918	0.04140	0.0151	doubtful
Radio Interval	0.00364	-0.00362	0.01091	0.0043	doubtful
Pilot Interval	0.02425	-0.04149	0.08999	0.0394	poor
Alarm Delay	-0.00147	-0.00686	0.00391	0.0032	poor

Table 34: Regression Analysis to determine parameters fitting
hazard = a * turb + b * radio_interval + c* pilot_interval + d * alarm_delay
to TRACON scenarios in which the loss of separation exceeds 5% of the desired separation.

This scenario was very well solved (the vast majority of even the "unreasonable" cases included). The two exceptional "reasonable" cases were for one aircraft maneuvering and had hazard values of 0.11 and 0.12.

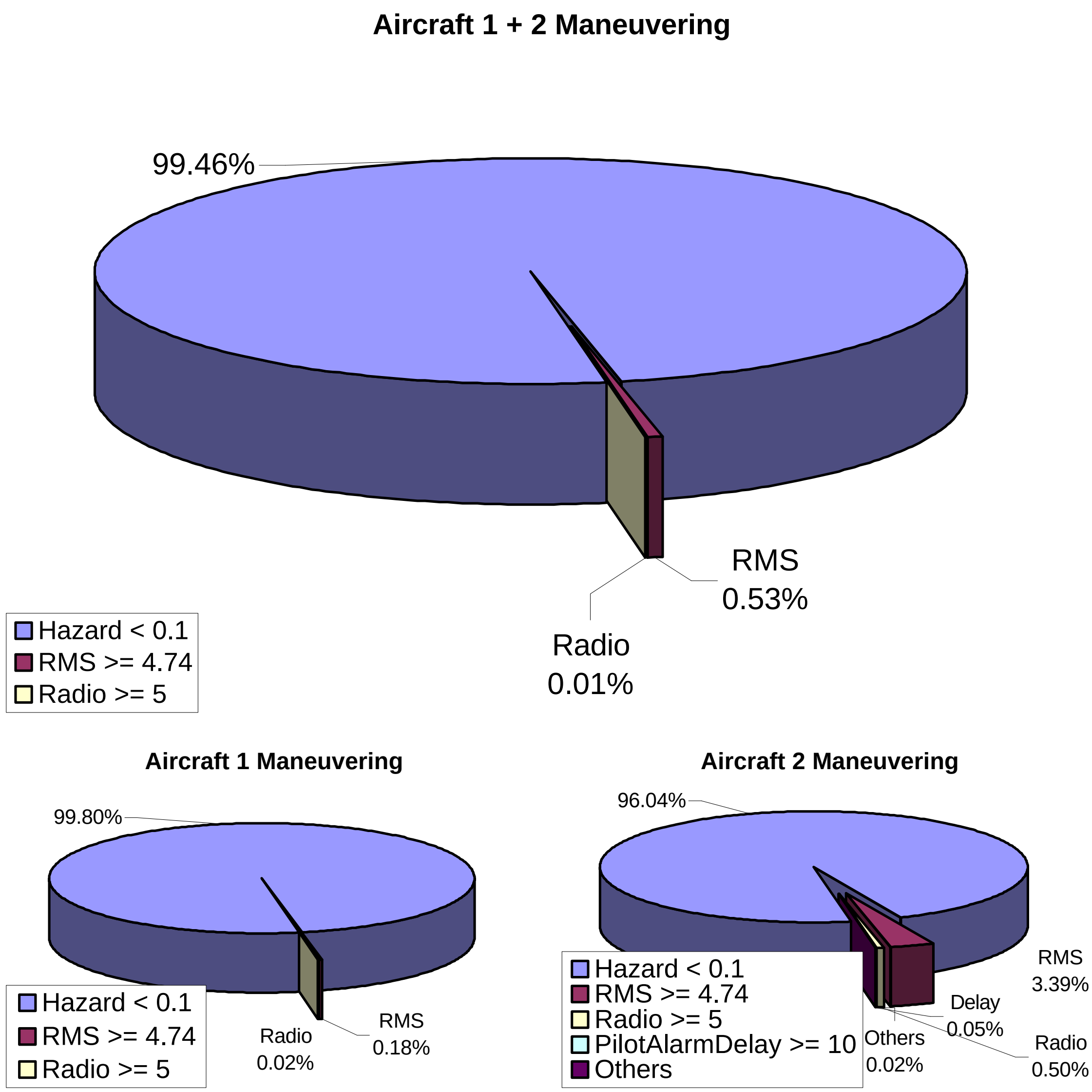


Figure 37: TRACON Resolution Attribution

Radio Interval	Pilot Interval	Pilot Alarm Delay	Turb RMS	Alert Time	Hazard
4.2677	3.0135	7.0271	3.4518	40.02009	0.112203
2.8741	1.6057	4.782	4.2768	78.27383	0.124424

Table 35: Cases of "Aircraft 2 Maneuvering" for which Hazard exceeds 0.1.

2.5.10.2.5 En Route Scenario

Note: No regression analysis is provided as the six points above 0.1 were not sufficient to perform a meaningful linear fit.

The conflict resolution in the en route case is excellent when both aircraft maneuver. Indeed, it would have been appropriate to examine even more *unreasonable* parameters (e.g. alarm delay of 30 or 45 seconds and radio intervals of 20 seconds or more) to learn just where the en route scenario started to break down with both aircraft maneuvering. Observations:

1) The solutions were not so good when only one of the aircraft maneuvered. One percent and 3%, respectively, of the aircraft 1 only and aircraft 2 only scenarios failed.

2) The scenario was nearly head-on. We may expect that performance would have been even better if the conflict orientation had been less demanding, e.g. a right angle or acute angle approach.

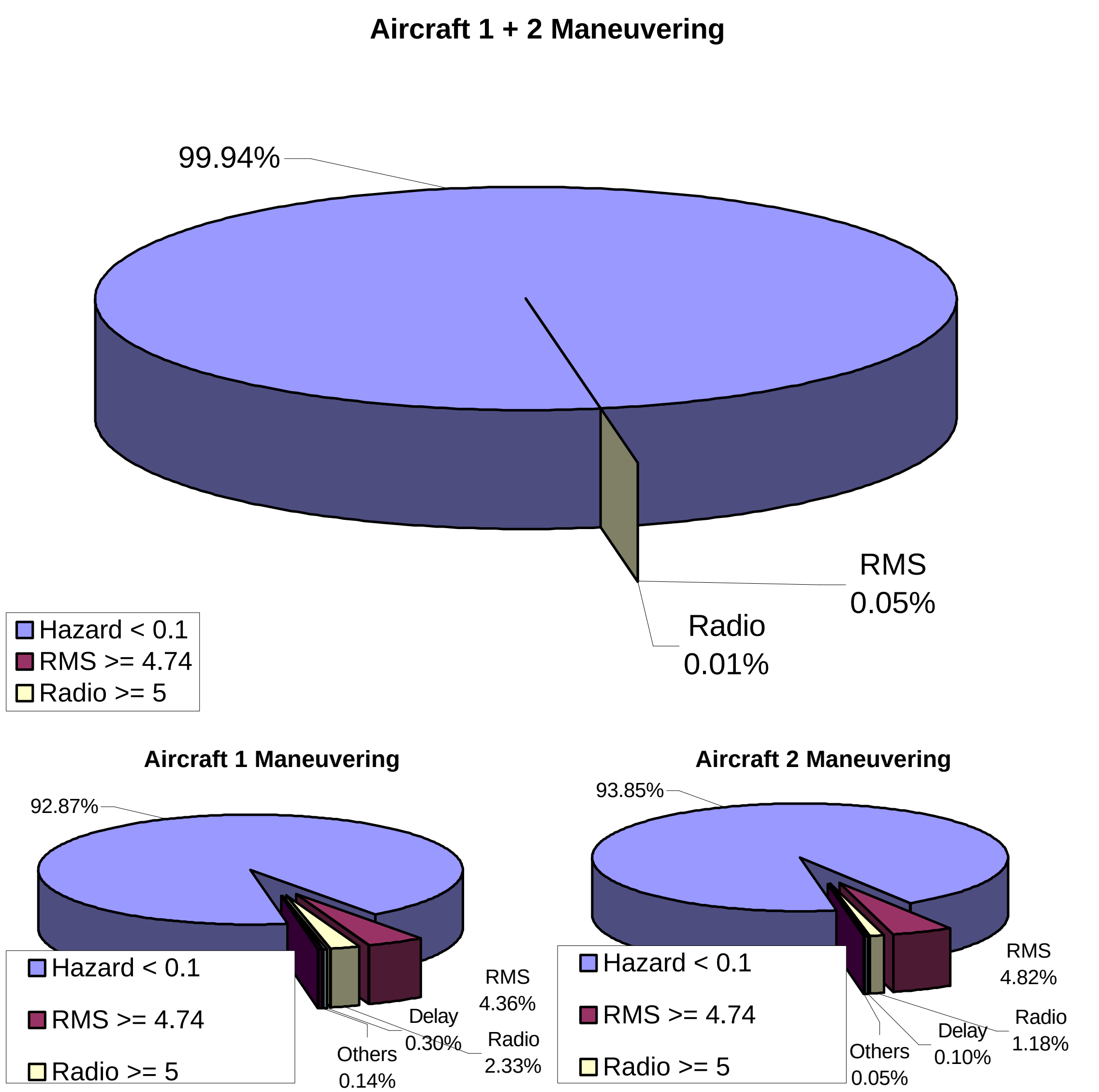


Figure 38: En Route Resolution Attribution

Radio Interval	Pilot Interval	Pilot Alarm Delay	Turb RMS	Alert Time	Hazard
3.8055	1.5807	5.2344	3.7024	107.8477	0.121896
3.0478	3.5849	2.9766	3.7905	91.44335	0.124656
2.845	1.292	3.2232	3.3174	112.6437	0.142355
4.8978	4.308	2.9916	3.089	99.27915	0.155879
3.3476	4.9704	7.1258	4.2686	86.88991	0.181744
2.2639	1.6806	8.9963	4.1936	109.6552	0.182372
4.6136	4.6124	6.5459	3.3382	106.6051	0.182722
3.3345	4.1985	4.7076	3.6458	105.9081	0.183186
2.5131	2.3538	3.1389	2.3811	106.2101	0.185647
3.1083	3.3988	8.3978	3.8351	94.83964	0.189605
4.8208	1.8522	8.3007	4.6717	118.6832	0.211672
3.8777	2.6003	2.2625	3.3961	96.03786	0.250901
2.3435	1.9962	8.3857	4.6189	91.23152	0.262465
2.3234	4.7923	5.0033	4.0356	78.03759	0.492624

Table 36: Cases of "Aircraft 1 Maneuvering" for which Hazard exceeds 0.1.

Radio Interval	Pilot Interval	Pilot Alarm Delay	Turb RMS	Alert Time	Hazard
2.3546	4.1843	8.7961	4.426	65.49102	0.119345
4.4346	4.4698	6.5088	4.6398	94.02337	0.149347
4.9961	3.2848	3.0858	4.5138	98.14777	0.15176
2.3027	3.3863	7.4331	3.7555	111.2412	0.236344
2.8696	4.7894	6.4062	3.9624	88.58885	0.255581

Table 37: Cases of "Aircraft 2 Maneuvering" for which Hazard exceeds 0.1.

2.5.10.2.6 Close VFR Scenario

Conflict resolution for this scenario was very good, roughly 99% of runs being solved to a hazard level of 0.1 or less.

Parameter	Estimate	90% low	90% high	std error	Applicable
Turbulence	0.00696	0.00182	0.0121	0.0031	high
Radio Interval	0.00853	0.00569	0.0113	0.0017	extreme
Pilot Interval	0.00766	-0.0069	0.0222	0.0088	doubtful
Alarm Delay	0.00449	0.00225	0.0222	0.0013	high

Table 38: Regression Analysis to determine parameters fitting hazard = a * turb + b * radio_interval + c* pilot_interval + d * alarm_delay to Close VFR scenarios in which the loss of separation exceeds 5% of the desired separation.

The close VFR scenario used the smallest protected airspace zone of any of them, 0.2 nautical miles and 300 feet compared to as much as 5 nautical miles and 1000 feet for the En Route scenario. Because hazard is measured as a fraction of the desired separation, the Close VFR scenario is particularly sensitive to small (absolute) penetrations of the protected zone. The effect is visible in the overall parameter vs. hazard charts (Figure 29 through Figure 32. The effect is not, however, particularly visible in the pie charts below. Comments:

1) The largest factors in failed resolutions (hazard > 0.1) was pilot alarm delay, followed by ADS-B interval. This isn't surprising since the small protected zone led to the smallest conflict alarm lead times.

2) In all three equipage scenarios, there were only two cases of hazard greater than 0.1 among the simulations which had "reasonable" parameters. Both of these occurred when only the least maneuverable aircraft was permitted to resolve the conflict.

3) Recall that this scenario was different from the others in that it did not have a fixed geometry. Instead, a random conflict generator was used to create conflicts with the aircraft approach on random headings with random climb/descent rates. The lack of resolution failures is strong evidence that the implicit coordination of maneuvers between aircraft is effective for all conflict orientations.

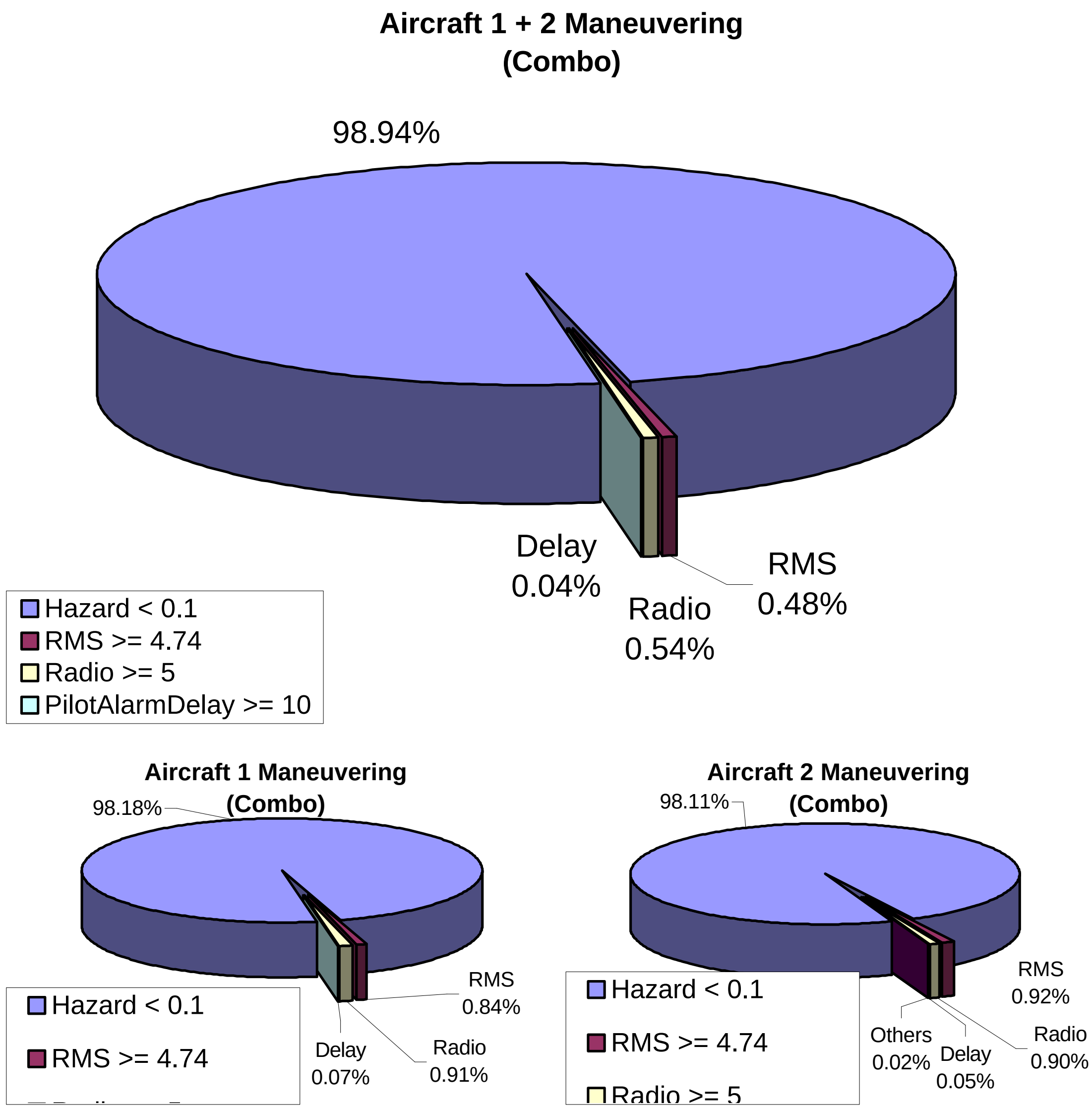


Figure 39: Small Zone Scenario Resolution Attribution

Radio Interval	Pilot Interval	Pilot AlarmDelay	Turb RMS	AlertTime	Hazard
2.3052	2.1569	9.5501	3.076	15	0.171367
4.9417	1.7679	9.1257	2.4956	48.63073	0.441283

Table 39: Cases of "Aircraft 2 Maneuvering" for which Hazard exceeds 0.1.

2.5.11 Conclusions

This work attempted to consider the important aspects of Airborne Conflict Management. Factors ranging from turbulence to pilot attentiveness were considered.

2.5.11.1 Feasibility

ACM appears to be *entirely* feasible. This study has shown that ADS-B surveillance requirements hypothesized by RTCA to be suitable for ACM are sufficient. The study has demonstrated that implicit coordination is entirely feasible. Finally, the study has examined conflict scenarios ranging from high-rate-of-closing en route scenarios with large protected airspace zones to random conflict orientations with extremely small protected airspace zones and found that ACM is practical for all of them.

2.5.11.2 Conflict Detection Algorithm

The conflict detection algorithm, specifically designed for this study, appears to have an extremely low nuisance alarm rate. It may well be, however, that the algorithm could be tuned to provide greater advance notice of conflicts at the expense of more numerous nuisance alarms without necessarily increasing the perceived nuisance.

It is possible that pilots might be concerned/annoyed that the alert is not presented on targets that they feel do represent a threat. Learning the best tuning for ACM conflict detection algorithms will almost certainly take real-world experience. This study demonstrated a workable conflict detection algorithm that was tuned very conservatively.

2.5.11.3 Resolution Algorithms and Implicit Coordination

The conflict resolution algorithms used in this work use implicit coordination. The aircraft transmit their position and other information via ADS-B, but no two-way communication is used to coordinate particular maneuvers. Instead, implicit rules are followed based on the encounter geometry and parameters. The algorithms provided practical conflict resolution and coordination.

2.5.11.4 State Vector vs. Trajectory Change Points

This work has demonstrated that utilizing the velocity state vector (the aircraft's instantaneous 3-dimensional velocity) is sufficient for conflict detection and resolution. The state vector alone is enough to provide safe flight. It is, however, extremely likely that Trajectory Change Points (TCPs), if available, could be used to further intelligently filter out nuisance alarms in those cases where aircraft state vectors are in conflict but one or more of the aircraft involved does not intend to maintain its current trajectory.

2.5.11.5 Safety

Of the nearly 10,000[5] "reasonable" cases studied, only 65 (about 0.7%) exceeded a hazard level of 0.1. None violated the desired separation by as much as half. The ACM conflict detection and resolution algorithms utilized in this study are robust. The algorithms continue to work to provide the greatest separation possible even in cases where the entire desired separation has been lost and/or cannot be attained.

[5] This analysis specifically excludes the "insoluble" slow aircraft maneuvering in the high/low scenario.

2.5.12 Required Surveillance Performance

2.5.12.1 Radio range

This study did not attempt to determine a minimum radio reception range necessary to perform ACM. Rather, it simply utilized a radio range model more conservative (i.e. with lower performance) than a proposed ADS-B link mechanism. Because the simulations were successful even with this model, we may assert that a satisfactory (but not necessarily *minimum)* RSP for radio broadcast/reception specifies that, for any single broadcast/receive attempt, the probability of reception vs. range function exceeds:

$$\mathrm{Prob}_{\mathrm{recv}} = 1 - (\mathrm{dist}_{\mathrm{XY}}/90\mathrm{NM})^3:$$

2.5.12.2 ADS-B Interval

This study investigated radio broadcast intervals ranging from 2 seconds to 16 seconds and found that a broadcast interval of 5 seconds was sufficient for ACM purposes. Note that the broadcast interval should not be confused with the reception interval, the latter being a function of the broadcast interval and the probability of reception.

2.5.12.3 Pilot alarm delay

The effect of delay on the achieved conflict resolutions was incremental; there was no apparent discontinuity in the relationship between the amount of time which passed before the pilot responded to a conflict alert and either level of hazard or the frequency with which the hazard exceeded 0.05. Ten seconds was found to be sufficient to provide the results described in this document even with the conservative natures of conflict alerting algorithm and radio broadcast models used in the simulations.

2.5.12.4 Piloting Interval

Across the 1 to 5 second range studied, the piloting interval (the frequency with which course corrections were applied) was not a significant factor in the success of resolutions. A piloting interval of 4 or 5 seconds is sufficient.

2.5.12.5 Position Error

Position error was found to somewhat *improve* achieved separation, so long as the error was known and included in the total measured spacing to be achieved. This results from the fact that the size of the protected space was always increased, in every direction, by the absolute maximum error, but the *actual* error was always smaller *and* in only one direction at any given time.

2.5.12.6 Velocity Error

Velocity error did not play a perceptible role in achieved conflict resolutions since the effect of velocity error on conflict point-of-nearest-approach calculations becomes nil as the conflict evolves. Large velocity errors (e.g. 20 knots or 100 vertical fpm), would, of course have a more significant impact on nuisance/missed alerts.

2.5.12.7 Turbulence

While not a *surveillance* parameter, turbulence is does have a very strong effect on the aircraft's velocity state vector and, hence, on the detection of conflicts. This work has demonstrated that conflict detection and resolution is practical even in heavy turbulence (up to 4.74 knots RMS). Since pilots generally seek to avoid even moderate turbulence, it should be an extremely rare occurrence that an aircraft would experience turbulence beyond that investigated in this work. It seems even more unlikely that two aircraft would both fly into/through such turbulence on conflicting vectors. Turbulence does not prevent effective ACM when the velocity state vector is used to predict conflicts.

3 Summary of Requirements

The following table summarizes the ACM requirements related to the Monte Carlo analysis, safety analysis, and ADS-B MASPS (RTCA DO-242A). These proposed requirements for nominal performance of installed equipment do not preclude the use of the ACM application in operational cases of degraded performance as long as the level of degradation is known and the system is able to maintain the target level of safety.

Requirement	Nominal Minimum Performance*	Justification for Requirement	Related Section numbers
Navigation Accuracy Category-Position (NAC_p)	NAC ≥ 7 Estimated Position Uncertainty (95%) less than 0.1 NM	Not a requirement, but in practice this NAC will be met if the NIC ≥ 7 requirement is met	2.4.4.3
Navigation Accuracy Category-Velocity (NAC_v)	$NAC_v \geq 2$ Estimated Velocity Uncertainty < 3 m/s; Vertical Estimated Velocity Uncertainty < 15 ft/s	Simulation Results	2.5.1 2.5.10.1.6
Navigation Integrity Category (NIC)	NIC ≥ 7 Radius of containment less than 0.2 NM	Engineering judgment for practical application of ACM	2.4.4.3
Surveillance Integrity Level (SIL)	SIL ≥ 2 10^{-5} per flight hour	Fault tree safety analysis	Figure 10 Figure 15 2.4.4.2
Altimetry Quality (Integrity bound, Integrity level)	± 800 to 1200 feet, 10^{-5} per flight hour	Engineering judgment based on consideration of RVSM, achievable altitude-keeping tolerance, and an increased tolerance for common altimetry systems.	2.4.4.4.4
ADS-B Update Rate	One every 5 seconds	Simulation Results	2.5.1 2.5.12.2
Coverage Range	Approaching 90 NM as described by the modeled probability of reception of one message: $P = 1-(dist/90NM)^3$	Simulation Results	2.5.3.6.1
Range corresponding to 95% probability of	60 NM	Simulation Results	Figure 21

reception in 12 seconds (based on 5 second ADS-B Update Rate)			

*Note: The Nominal Minimum Performance is required for certification of an ACM system. However, ACM will continue to function with reduced quality data, subject to practical limits. For example, if the primary navigation system fails and an aircraft reverts to a secondary system with a NIC value of less than 7, ACM will work to maintain or regain the necessary separation.

Table 40: Summary of ACM Requirements